Modeling and Analysis of Phosphorus Reduction by Rain Gardens and Other BMPs in Stormwater Runoff from Small Urban Developments

By

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ABSTRACT

As part of *The Discovery Museums (TDM) Low Impact Development (LID) Design and Monitoring* report (Master of Engineering Group Project) for the town of Acton, , the effectiveness of low impact development technologies at improving the quality of stormwater runoff from TDMs parking lot was evaluated. Several Best Management Practices (BMPs) and LID technologies were assessed to determine which devices would be most suitable for the site. The P8 Urban Catchment Model was chosen to model phosphorus concentrations in stormwater runoff before and after the implementation of LID. The results were then assessed to determine whether or not these technologies significantly improve the runoff water quality.

In this thesis, the analysis is extended to assess the improvement in phosphorus concentrations if rain gardens are implemented on a fraction of residential areas in the Nashoba Brook watershed. The effectiveness of a rain garden at improving the phosphorus concentrations in runoff was evaluated by modeling the device in P8.

Both the TDM site analysis and the Nashoba Brook hypothetical analysis yielded results with significant reduction in total phosphorus loading. These results should encourage further research on the widespread use of LID.

Thesis Supervisor: Peter Shanahan
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1 Introduction

According to the Massachusetts Department of Environmental Protection (MDEP), the Assabet River is identified in the 1998 303(d) listing and the 2002 Massachusetts Integrated List of Waters as impaired primarily for nutrients, organic enrichment and low dissolved oxygen (DiBara). In 2001, a field study of the Assabet River system was conducted by ENSR to investigate nutrient loadings and the interrelationship between nutrients and aquatic vegetation in the system. The study confirmed that the Assabet River receives an excess of phosphorus and nitrogen resulting in excessive growth and eutrophication. Phosphorus is actually the primary nutrient known to accelerate eutrophication in freshwater systems. In order to prevent further degradation in water quality of the Assabet River, a Total Maximum Daily Load (TMDL) for total phosphorus was established, based on data collected in 1999 and 2000. Meeting the TMDL will require decreased loadings from publicly owned treatment works (POTWs) and from certain non-point sources (MDEP 2004a). This study attempts to use rain gardens and other best management practices as ways to minimize the contribution of total phosphorus in stormwater runoff from non-point sources, specifically from residential land use. Since runoff from residential developments eventually discharges into the Assabet River, improved water quality of the runoff is directly related to improved water quality of the river.

1.1 *Assabet River Overview*

The Assabet River has a length of 31.8 miles and drains an area equal to 178 square miles (see). It flows from its source in Westborough to its confluence with the Sudbury River in Concord (Wadsworth 2000). The watershed encompasses contains nine tributaries and over 170,000 people reside in the watershed (OAR 2005).

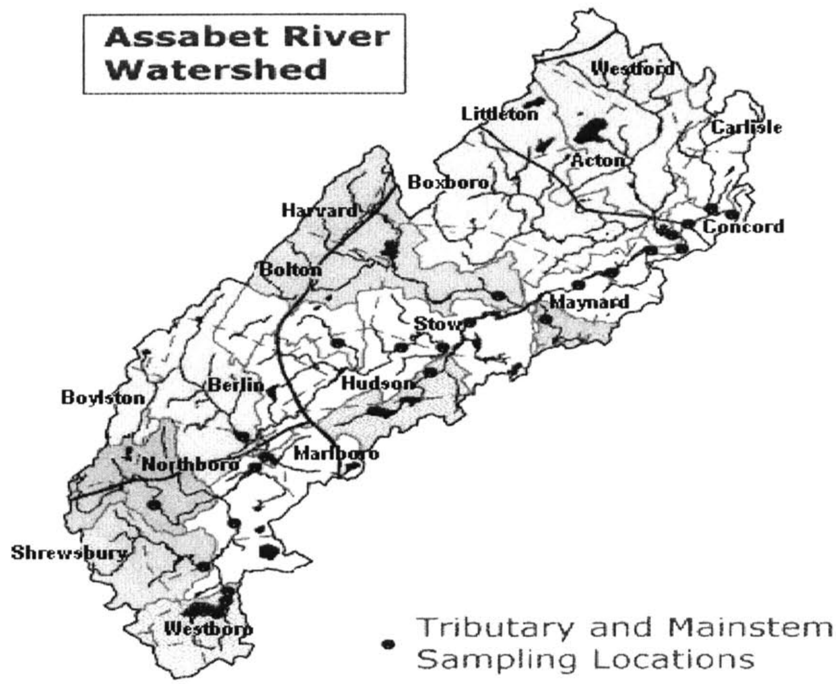

Figure 1: Assabet River Watershed (OAR 2005)

1.2 *Problem Assessment*

The Assabet River receives an excess of phosphorus and nitrogen loading which results in excessive growth and eutrophication. One of the reasons for the impairment, particularly in increased total phosphorus nutrient loading, is due to four publicly owned treatment works (POTWs) that discharge treated wastewater into the river. These four POTWs are located in Westborough, Marlborough, Hudson, and Maynard (MDEP 2004a). Another reason for the impairment is due to increasing groundwater extraction in the Assabet River watershed, which has reduced the contribution from underlying aquifers to the base flow of the river. (Assabet Issues).

Conventional stormwater management systems have also amplified the problem of decreased aquifer recharge, baseflow, and poor water quality. These systems were designed with a primary objective of quickly removing runoff from streets and sidewalks. . However, the total volume of runoff is not controlled, resulting in increased flooding downstream and decreased aquifer recharge. Additionally, runoff controlled by traditional best management practices (BMPs) often is discharged directly to streams or other water bodies without any treatment. Urban runoff contains pollutants such as suspended solids, nutrients, toxics, and bacteria. When the runoff enters the river it exacerbates the problem of poor water quality.

1.3 *Nonpoint Source Control Using LID*

As a result of land development, conventional stormwater management systems were designed with the aim to quickly remove runoff from streets and sidewalks through the use of facilities such as storm sewers, curbs, and gutters. This approach removes peak flow resulting from small storms fairly fast. However, there are water quality concerns associated with runoff that is washed off from paved and impervious surfaces. The high speed of runoff keeps pollutants such as sediments, nutrients, chemicals, and disease-carrying organisms suspended in the runoff. These pollutants thus end up being discharged into streams or other receiving water bodies. Sources of these pollutants include grass clippings, eroded soil, fertilizer, oil and gasoline drippings, animal droppings, and atmospheric deposition. As a result of the impact of urbanization and conventional stormwater management on water quantity and quality, low impact development (LID) was adopted in an effort to mitigate these adverse effects (Sykes 1998).

LID is an innovative approach to stormwater management with a basic principle that is modeled after nature: manage rainfall at the source using uniformly distributed decentralized micro-scale controls. LID's goal is to mimic a site's predevelopment hydrology by using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source while filtering and decreasing pollutant concentrations through filtration, biodegradation, and other natural processes (LID Center Inc.).

1.4 *Case Studies*

Two case studies were developed to investigate if any water quality improvement is achieved by implementing LID and BMPs to manage runoff from small suburban sites. The first case study aimed to evaluate the effectiveness of rain gardens as decentralized technologies to manage and improve stormwater quality at residential developments. The second case is part of the Master of Engineering (MEng) group project for The Discovery Museums which are located in the town of Acton, Massachusetts, Its aim was to design a site retrofit to increase parking capacity and manage stormwater runoff using LID (Brown et al. 2005).

2 Low Impact Development

LID is a relatively new practice that attempts to unite site planning, land development, and stormwater management with ecosystem protection. It was first developed in the 1990s in response to the economic and environmental impacts of conventional stormwater management techniques. In essence, LID is a comprehensive development and design technique that strives to preserve the pre-developed ability of a site to manage rainfall through a series of small-scale, distributed structural and non-structural controls. LID devices capture water on site, filter it through vegetation, and let it soak into the ground where it can recharge the local water table rather than being lost as surface runoff. An important LID principle includes the idea that stormwater is not merely a waste product to be disposed of, but rather that rainwater is a resource (MDEP 2004b). Conventional development techniques often clear all trees and valuable topsoil from a site and re-grade it so that all water ends up in one large detention basin. Resulting problems include loss of recharge, increased water temperature, decreased water quality, and higher runoff volumes. The LID approach protects the natural ability of the site to capture precipitation, keep it clean and allow it to recharge the local water table. There are several LID technologies that can be applied to retain and improve the quality of water on-site. The two major classes are a) ponds and b) vegetative biofilters and they are summarized below.

2.1 *Ponds*

There are three types of pond BMPs: wet ponds (also known as retention ponds), dry ponds (also known detention ponds), and infiltration basins. Below is a description of each:

Wet Ponds/Retention Ponds

These are small artificial lakes with a permanent pool of water designed to capture runoff and remove pollutants from stormwater (see Figure 2). The main mechanism of treatment is achieved by the settling of suspended solids and nutrients and algal uptake of dissolved nutrients. Further treatment can occur in the water that resides in the pond in the interval between storms (USEPA 2002).

Figure 2: Wet/Retention Pond (ARC undated)

Dry Ponds/Detention Ponds

These are stormwater basins designed to intercept a volume of runoff and temporarily impound the water (e.g. 24 hours) for gradual release to the receiving stream or storm sewer system. A cross section is shown in Figure 3. In the early 1980's, the flow out of the dry ponds was restricted so that a pool of stormwater would be detained in the ponds for much longer periods of time. This new approach to dry ponds is called extended detention ponds. Extended detention ponds are designed to extend the time required for stormwater control to provide water quality improvement. They are best at removing settleable solids and associated pollutants (USEPA 2002).

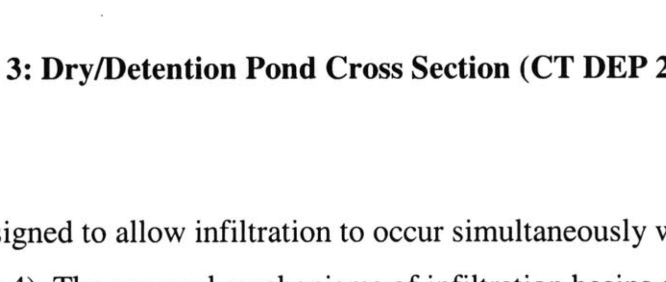

Figure 3: Dry/Detention Pond Cross Section (CT DEP 2004)

Infiltration Basins

These are dry ponds designed to allow infiltration to occur simultaneously with other removal mechanisms (see Figure 4). The removal mechanisms of infiltration basins are similar to those of the dry ponds except for a few exceptions. The main difference related to water quality is that infiltration basins remove suspended and colloidal solids in the volume of infiltrated water, whereas extended detention ponds can only remove the fraction of colloidal solids sorbed to settleable solids (EPA 2002).

Figure 4: Infiltration Basin (Syar 2003)

2.2 *Vegetative Biofilters*

Biofilters are used to reduce runoff impacts, recharge groundwater, and control water quality. There are three different types of vegetative biofilters and these are: swales, rain gardens or bioretention cells, and vegetative filter strips.

Swales

Swales are vegetated open-channel drainage structures used to convey stormwater runoff and allow filtration of pollutants (see **Figure 5**). They do not pond water for a long period of time nor induce infiltration. There are three types of swales: traditional grass swales, grass swales with media filters, and wet swales, which are described below (USEPA 2002).

Figure 5: Swale (Rhodes)

Traditional Grass Swales

Traditional grass swales, as shown in Figure 6, are shallow channels covered with vegetation that have a number of desirable attributes with respect to total stormwater management including:

- Slower flow velocities than pipe systems that result in longer times of concentration and corresponding reduction of peak discharges;
- Ability to disconnect connected impervious surfaces, such as driveways and roadways, thus reducing discharge;
- Filtering of pollutants by grass media;
- Infiltration of runoff into the soil profile thus reducing discharges, providing additional pollutant removal, and increasing groundwater recharge; and,
- Uptake of pollutants by plant roots (phytoremediation) (USEPA 2002).

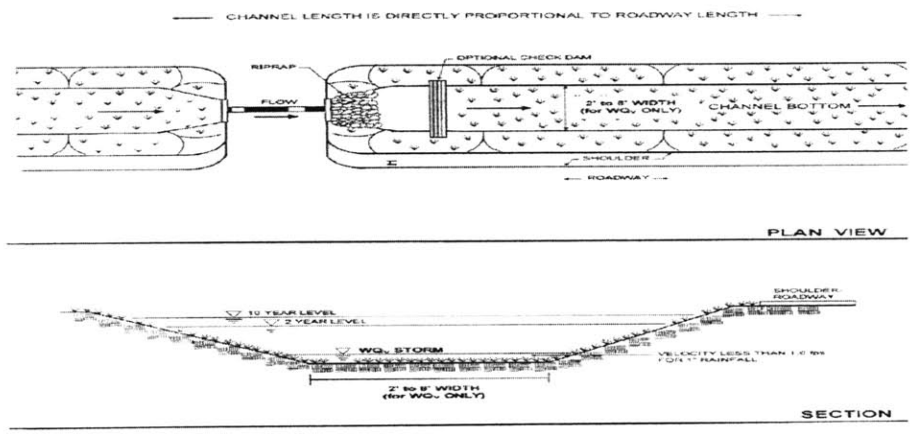

Figure 6:Traditional Grass Swale (Clar et al. 2004)

Grass Swales with Media Filters

This grass swale consists of an open channel that has been modified to enhance it water quality treatment capability by adding a filtration medium consisting of a soil bed with an underdrain system (see Figure 7). It temporarily stores water and allows it to percolate through the treatment medium. The water quality treatment mechanisms are similar to bioretention cells except that the pollutant uptake is likely to be more limited since only a grass cover crop is available for nutrient uptake (USEPA 2002).

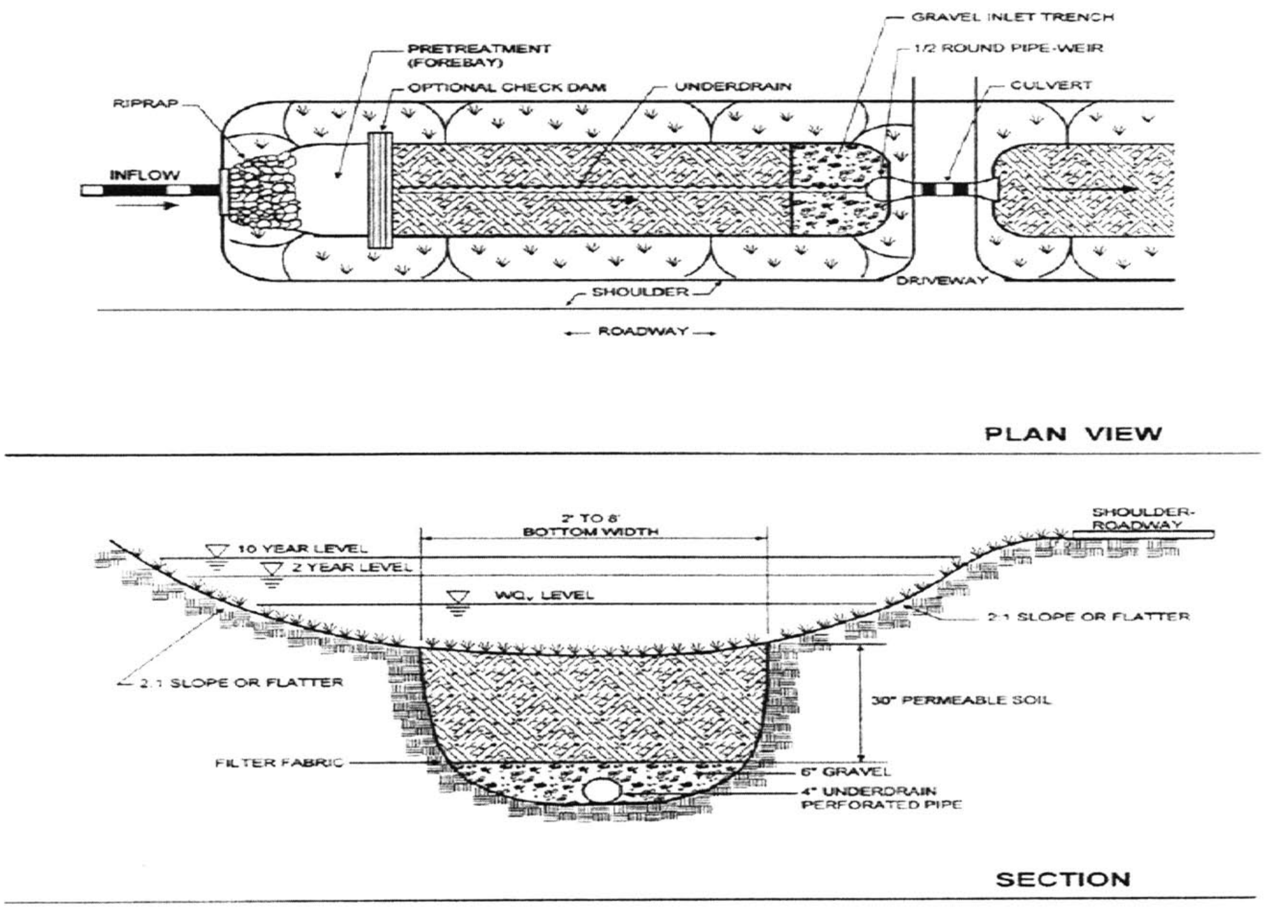

Figure 7: Grass Swale with Media Filters (Clar et al. 2004)

Wet Swales

These consist of a broad open channel capable of temporarily routing and storing water but which do not have an underlying filtering bed (see Figure 8). They are constructed directly within existing soils and may intercept the water table. The stormwater within the wet swale should be stored for approximately 24 hours. The water quality treatment mechanisms of the wet swale rely mostly on particle settling, adsorption, and uptake of pollutant by vegetative root systems (USEPA 2002).

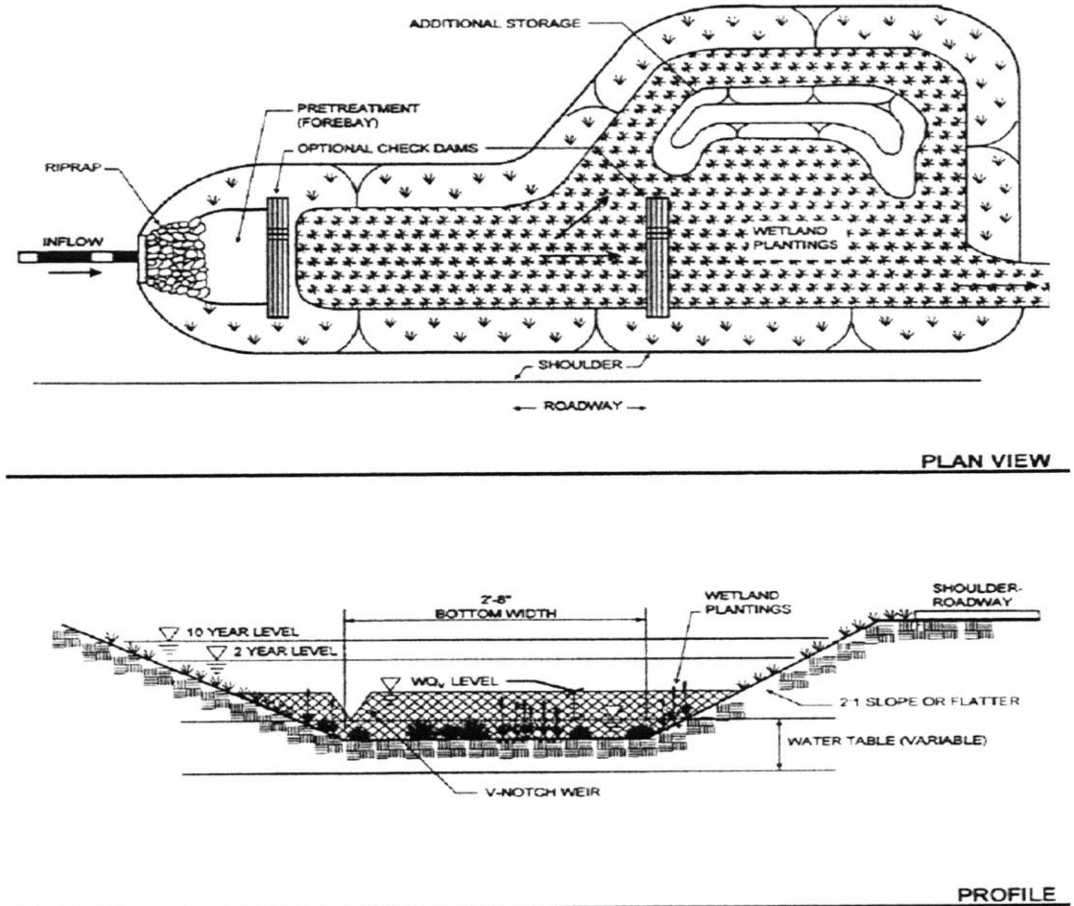

Figure 8: Wet Swale (Clar et al. 2004)

Rain Gardens/Bioretention Cells

Rain gardens manage and treat stormwater runoff through a variety of physical, biological, and chemical treatment processes. Stormwater is directed to shallow topographic depressions shown in Figure 9 and is filtered, stored, and infiltrated into the ground. These facilities usually consist of a grass buffer, conditioned planting soil bed, organic or mulch layer, and planting materials to filter runoff stored within a shallow depression. Both adsorption and chemical, biological, and physical filtering take place (USEPA 2002).

Figure 9: Bioretention Garden (Rhodes)

Vegetative Filter Strips

These are areas of land with vegetative cover that are designed to accept runoff as overland sheet flow from upstream development as depicted in Figure 10 . Dense vegetative cover facilitates sediment attenuation and pollutant removal for the design storms. Grading and level spreaders can be used to create a uniformly sloping area that distributes the runoff evenly across the filter strip. For small storms that do not discharge, infiltration becomes the primary removal mechanism (USEPA 2002).

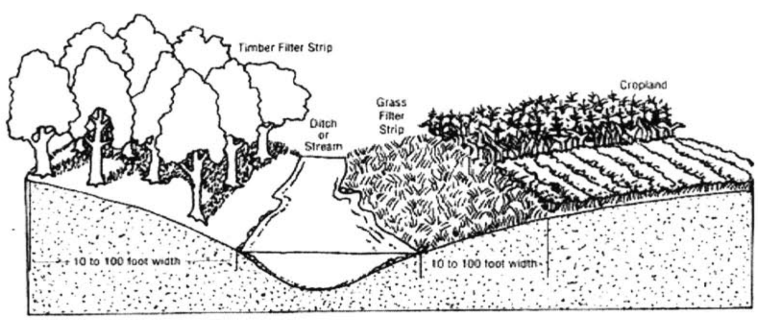

Figure 10: Vegetative Filter Strip (Leeds et al.)

3 Programs Available for LID and Water Quality Modeling

A program capable of modeling water quality and specifically phosphorus concentrations, in addition to analyzing LID and BMP devices, was needed. The criteria for program selection included:

- Ability to predict the impact of LID and BMP devices on non-point source pollutant removal
- Ability to simulate snowfall and snowmelt
- User-friendly interface
- Reliable results

3.1 *Programs Available for Water Quality Modeling*

The programs that were researched are SWMM, P8, HSPS, and BASINS. Summaries of each program's capabilities are described below:

3.1.1 Storm Water Management Model (SWMM)

SWMM is a dynamic rainfall-runoff simulation model, primarily used for urban areas, for single-event, or long-term (continuous) simulation. Nonpoint source runoff quality and routing can be simulated, as well as storage, treatment and other BMPs (James 2004). Technical limitations include lack of subsurface quality routing (a constant concentration is used), no interaction of quality processes (apart from adsorption), difficulty in simulation of wetlands quality processes (except as can be represented as storage processes), and a weak scour deposition routine in the Transport Block. The biggest impediment to model usage is the user interface, with its lack of menus and graphical output (Yoon 2004).

3.1.2 Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds (P8 Urban Catchment Model)

P8 is a model for predicting the generation and transport of stormwater runoff pollutants in urban watersheds. The model is used to evaluate runoff treatment schemes for existing or proposed urban developments. Some of the predicted water quality components include suspended solids (five size fractions), total phosphorus, total Kjeldahl nitrogen, copper, lead, zinc, and total hydrocarbons. Simulated BMP types include detention ponds (wet, dry, extended), infiltration basins, swales, and buffer strips. P8 Version 2.0 can also simulate snowfall and snowmelt (Palmstrom and Walker 1990).

3.1.3 Hydrological Simulation Program - FORTRAN (HSPF)

This model can simulate the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. The result of this simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed. Data needs for HSPF can be extensive. HSPF is a continuous simulation program and requires continuous data to drive the simulations. At a minimum, continuous rainfall records are required to drive the runoff model and additional records of evapotranspiration, temperature, and solar intensity are desirable (USEPA undated).

3.1.4 Better Assessment Science Integrating Point and Nonpoint Sources (BASINS)

BASINS is a multipurpose environmental analysis system designed for performing watershed and water quality-based studies. Large amounts of point source and non-point source data can be quickly assessed in a format that is easy to use and understand. BASINS allows the user to evaluate water quality at selected stream sites or throughout an entire watershed. It integrates environmental data, analytical tools, and modeling programs to support development of cost-effective approaches to watershed management and environmental protection, including total maximum daily limits. (USEPA, 2001).

3.2 *Model Selection*

The capabilities of each program are summarized below:

SWMM

- Primarily for urban areas
- Simulates nonpoint source runoff quality, storage, and BMPs
- Unfriendly user interface (lacks graphics and menus)

P8

- Water quality routing (pollutographs/loadings)
- Excellent output display
- Limitations primarily related to hydrology

HSPF

- Not menu driven
- Extensive data requirements
- Requires continuous rainfall records

BASINS

- Facilitates examination of environmental information
- Integrated watershed modeling framework
- Analysis of point and nonpoint source management alternative

P8 seems to be the most appropriate modeling approach for many reasons mainly that it was designed to predict the impact of BMPs on nonpoint source pollutant removal and has a friendly user interface. It can also simulate snowfall and snowmelt which will play a significant role on the quality of the stormwater. Therefore, P8 will be used to model the water quality for this project.

4 P8 Basic Program Details

P8 predicts the generation and transport of pollutants using continuous water-balance and mass-balance calculations. The user defines the system to be modeled by the using the four elements which are watersheds, devices, particle classes, and water quality components. It works by simulating continuous hourly rainfall and daily air temperature time series.

4.1 *Model Inputs and Mechanics*

Input data for the program includes the following elements with the following maximum dimensions for each:

192 watersheds

48 devices

5 particle classes and 10 water quality components

4.1.2 Watersheds

Watersheds are the sources of flow and particles to the devices and are defined based upon factors controlling runoff and particle export. These factors include total area, impervious fraction, depression storage, and SCS curve number. The model simulates runoff from pervious and impervious surfaces and particle buildup/washoff from impervious surfaces. Runoff and infiltration can be routed to specified devices. It is assumed that watershed runoff is transported directly to downstream devices without lag. Watersheds are usually referred to as basins. Particle concentrations in runoff from pervious areas are computed using empirical Equation 1:

Equation 1: Particle Concentration in Runoff

$$C_p = C_{po} I^f$$

where,

C_p = particle concentration in pervious runoff (ppm)

C_{po} = concentration at a runoff intensity of 1 inch/hr (ppm)
I = runoff intensity from pervious area (in/hr)

f = exponent based on typical sediment rating curves for rivers; values range from 0.1 – 1.6 with most values near 1.0

Particle loads from impervious areas are computed using particle accumulation washoff and/or fixed runoff concentration. The particle accumulation washoff is described by the differential Equation 2:

Equation 2: Particle Accumulation Washoff

$$\frac{dB}{dt} = L - kB - fsB - ar^{c}B$$

where,
B = buildup or accumulation on impervious surface (lbs/acre)
L = rate of deposition (lbs/acre-hr)
k = rate of decay due to non-runoff processes (1/hr)
s = rate of street sweeping (passes per hr)
f = efficiency of street sweeping (fraction removed per pass)
a = washoff coefficient
c = washoff exponent
r = runoff intensity from impervious surfaces (in/hr)

4.1.3 Devices

P8 can simulate the following seven stormwater control devices:

1 = Detention Pond (Wet, Dry, Extended)

2 = Infiltration Basin (Online, Offline)

3 = Swale/Buffer (Overland Flow Area)

4 = General (User-Defined Elevation/Area/Outflow Table)

5 = Pipe/Manhole (Collector with One Outlet)

6 = Splitter (Collector with Two Outlets)

7 = Aquifer (Approximates Groundwater Budget, Baseflow Calculations)

The devices collect, store, and/or treat runoff. Devices are defined based upon factors controlling hydraulic response and particle removal efficiency. Discharge can be routed to up to three outlets: 1 = infiltration, 2 = normal outlet, and 3 = overflow/spillway. Each device requires different input. Routing from one device to another is accomplished by specifying the downstream device numbers for each outlet. A downstream device number of 0 can be used to route the flow out of the system. The program keeps track of volume and mass fluxes into and out of each device as well as changes in storage. Flow and mass routing is performed in downstream order and the relationship between storage volume and outflow for each device and outlet is approximated by Equation 3.

Equation 3: Device Storage-Volume Relationship

$$Q = d_0 + d_1 V$$

where,

Q = outflow for a given device and outlet (ac-ft)

V = current device volume (ac-ft)

d_0 = intercept of outflow vs. storage volume curve (ac-ft/hr)

d_1 = slope of outflow vs. storage volume curve (1/hr)

Values of are d_0 and d_1 updated at each time step by interpolation from the elevation, area, volume, and outflow specified for each device. Since d_0 and d_1 may change with volume and elevation, a three-stage procedure is used to estimate the volume change at each time step:

$$V_m = V_1 + 0.5F(V_1, t)$$

$$V_2 = V_1 + F(V_m, t)$$

$$V_m = 0.5(V_1 + V_2)$$

where,

V_m = average volume during time step (ac-ft)

Device volumes are constrained to maximum values consistent with input data and excess flows are discharged through the "spillway" (device 3).

Water-balance and mass-balance checks are performed continuously on the entire network and a warning message is issued if continuity errors exceed the maximum value specified on the time step input screen. The errors can be reduced by specifying shorter simulation time steps. For this project five of the seven types of devices were used. The devices are the detention pond, infiltration basin, pipe/manhole, flow splitter, and aquifer.

4.1.3.1 Detention Pond

The main input data required for the pond are the surface area (must specify area for pond bottom, permanent pool, and flood pool), storage volume (for permanent pool and flood pool), infiltration rate, and outflow device numbers. If the flow into the pond exceeds the flood pool volume a normal outlet must be defined using one of four options:

- Orifice diameter and discharge coefficient
- Weir length and weir discharge coefficient
- Riser height, holes, hole diameter, and orifice discharge coefficient
- Flood pool drawdown time

The program assumes a linear relationship between volume and elevation for the detention pond. The user specifies the bottom area A_1 (with an implicit volume V_1 of zero), the permanent pool area A_2 and volume V_2, and the flood pool area A_3 and volume V_3. Linear interpolation utilizing the trapezoidal rule is executed to compute the relationship between volume and depth as follows:

$V_3 - V_2 = 0.5(A_2 + A_3) * H$ the equation is solved for the depth of the flood pool, H

$A(z) = A_2 + (A_3 - A_2) * z / H$ where z is depth above permanent pool height

$V(z) = (A_1 + A(z))/2 * z$

The outlet capacities are calculated from input dimensions using the weir and orifice formulae shown in Equation 4and Equation 5 (Palmstrom and Walker 1999).

Equation 4: Weir Outlet Capacity

$$q_w = c_w l_w h^{1.5}$$

Equation 5: Orifice Outlet Capacity

$$q_0 = c_0 a_0 (2gh)^{1/2}$$

where,

q_w = weir flow (cfs)

c_w = weir coefficient ~ 3.3

l_w = weir length (ft)

h = height above weir crest or above orifice centerline (ft)

q_0 = orifice flow (cfs)

c_0 = orifice coefficient ~ 0.6

a_0 = orifice area (ft^2)

g = acceleration of gravity

Only one controlled outlet, referenced as the "normal" outlet, can be defined for the flood pool of a detention pond. When the flood pool of a detention pond is full the "spillway" outlet is activated to pass excess overflows to the next device downstream.

4.1.3.2 Infiltration Basin

The data required for this device are the storage pool and bottom areas, void volume, infiltration rate of the saturated soil conditions, and overflow outlet. The outflow device number is set to "0" to direct overflow out of the system and "7" to route the exfiltrate to an aquifer.

4.1.3.3 Pipe/Manhole

This device can be used to collect outflows from a number of watersheds and/or devices and discharge them out of a system or to a specific device. A pipe is modeled as a linear reservoir defined by Equation 6: Linear Reservoir Equation (Olivera 1999). The power of the linear reservoir model is that the fraction of stored volume does not change in time; it does not depend on storage or flow (Olivera 1999). A pipe is also modeled with a specified time of concentration, t_c. If $t_c = 0$, outflow responds immediately to inflows. If $t_c \neq 0$, there is a delay between the response of device outflows to inflows. There is no particle removal in a pipe.

Equation 6: Linear Reservoir Equation (Olivera 1999)

$$\Delta V = [\, S(t) - S(t + \Delta t)]/\, S(t)$$

Where

ΔV = fraction of stored volume released in t

Δt = time increment

$S(t)$ = storage at time t

$S(t + \Delta t)$ = storage at time at $t + \Delta t$

4.1.3.4 Splitter

The splitter can be used to direct flows to either of two downstream devices depending upon whether the head in one of them exceeds the surface elevation. The splitter is modeled as a linear reservoir with a specified t_c. If $t_c = 0$, outflows respond immediately to inflows and if $t_c \neq 0$, there is a delay between the response time of device outflows to inflows. The splitter has no particle removal efficiency.

4.1.3.5 Aquifer

The aquifer device provides storage and discharge of percolation from pervious watershed areas. Equation 7 lists the mass balance used to estimate percolation:

Equation 7: Mass Balance Estimation of Percolation

$$\text{Percolation} = \text{Rainfall} - \text{Surface Runoff} - \text{Evapotranspiration}$$

The Soil Conservation Service (SCS) method is used to calculate surface runoff based on the curve number, CN. Evapotranspiration is estimated from the temperature and month. The predicted outflow from an aquifer approximates baseflow. The response time of an aquifer is modeled as a linear reservoir just like the above two devices and likewise does not remove particles or contaminants.

4.1.4 Suspended Sediment and Water Quality Components

Suspended sediment is an important pollutant that P8 addresses through mass balance for multiple particle classes. Table 1described the particle classes that are included in the particle input files distributed with the program,

Table 1: NURP Settling Velocity Distributions (Palmstrom and Walker 1990)

Class	Description	% TSS	Settling Velocity (ft./hr)
P0%	Dissolved	0	0
P10%	10th Percentile	20	0.03
P30%	30th Percentile	20	0.3
P50%	50th Percentile	20	1.5
P80%	80% Percentile	40	15

Particles are defined based upon factors controlling watershed export such as accumulation/washoff parameters for impervious areas and fixed runoff concentrations for pervious and/or impervious areas. Distribution of water quality components among particle classes is based upon results of direct runoff measurements, settling column tests, and typical pollutant removal efficiencies in treatment devices. For total phosphorus, 30% of the total runoff concentration is assumed to be associated with the dissolved particle class (P0%). A dissolved fraction of 40% is assumed for total Kjeldahl nitrogen, copper, and zinc. Non-dissolved portions of total phosphorus, Kjeldahl nitrogen, copper, and zinc are equally distributed among the three smallest particle classes (P10%, P30%, P50%).

The criteria included in the particle/component files are listed in Table 2 (Palmstrom and Walker 1990). They can be used to estimate violation frequencies, based upon comparison with the frequency distributions of event-mean outflow concentration for any device and storm sequence.

Table 2: Water Quality Criteria

Component (ppm)	Level A	Level B	Level C
Total Suspended Solids	5	10	20
Total Phosphorus	0.025	0.05 d	0.10 e
Total Kjeldahl N	2.0	1.0	0.5
Total Copper	2.0 a	0.0048 b	0.02 c
Total Lead	0.02 a	0.0140 b	0.15 c
Total Zinc	5.0 a	0.0362 b	0.38 c
Total Hydrocarbons	0.1	0.5	1.0

a- USEPA primary drinking water standard
b- Rhode Island standard, acute toxicity, fresh waters, hardness = 25 ppm
c- NURP threshold for aquatic life, intermittent exposure, soft waters (Athayde et al., 1983)
d- USEPA (1976) guideline for eutrophication in streams
e- USEPA (1976) guideline for streams entering lakes
Others are arbitrary benchmarks (no standards or criteria)

The water quality criteria specified in Table 2 are assigned to a receiving water body based on the water body's intended function and use. These criteria are described below.

Level A – "These waters are designated as a source of public water supply. To the extent compatible with this use they shall be an excellent habitat for fish, other aquatic life and wildlife, and suitable for primary and secondary contact recreation. These waters shall have excellent aesthetic value." (MDEP 2000).

Level B – "These waters are designated as a habitat for fish, other aquatic life, and wildlife, and for primary and secondary contact recreation. Where designated they shall be suitable as a source of public water supply with appropriate treatment. They shall be suitable for irrigation and other agricultural uses and for compatible industrial cooling and process uses. These waters shall have consistently good aesthetic value." (MDEP 2000).

Level C – "These waters are designated as a habitat for fish, other aquatic life and wildlife, and for secondary contact recreation. These waters shall be suitable for the irrigation of crops used for consumption after cooking and for compatible industrial cooling and process uses. These waters shall have good aesthetic value." (MDEP 2000).

4.2 *Filtration Efficiency*

The percent of each particle class removed when water infiltrates a device or pervious watershed area is assumed to be 100% for each suspended solids fraction (P10% - P80%). A filtration efficiency of 90% is assumed for the dissolved fraction (P0%) to account for adsorption, precipitation, and other reactions between dissolved runoff contaminants and the soil matrix. It is these reactions that are responsible for the low concentrations of phosphorus and heavy metals found in groundwater beneath swales and retention basins. With these parameter values the predicted total phosphorus concentrations in groundwater are approximately 0.01 ppm and the predicted average streamflow total phosphorus concentrations (baseflow plus runoff) range from 0.014 to 0.15 ppm.

4.3 *Limitations*

Runoff water quality is highly variable from site-to-site and from storm-to-storm at a given site and site-specific runoff quality data is generally not available particularly when dealing with future developments. This lack of data limits the accuracy of the model. The predicted results are accurate in a more relative sense than an absolute sense. That is, comparisons of the relative mass of contaminants between development scenarios are likely to be more accurate than the absolute predictions of mass. Additionally, P8 does not have a rain garden device so a logical sequence of several devices had to be used to model the rain gardens. This strategy generated reasonable results but it is unknown how accurate they are.

5 Rain Gardens

Rain gardens got their start in 1988 when Larry Coffman, Associate Director for the Department of Environmental Resources in Prince George's County, Maryland, thought "out of the box." After hearing about the practice of growing plants on septic system drainfields as a way to break down pollutants, Coffman thought of using onsite treatment and infiltration, known as bioretention, in an urban setting and called his idea a "rain garden." His rain garden design consisted of a shallow depression designed to collect runoff from impervious surfaces, such as roofs, and allow plants, bacteria, and soil to clean the water as it infiltrates into the ground. By keeping stormwater close to where it falls, rain gardens help reduce flooding and settle out sediments. At the same time, rain gardens prevent stormwater from becoming contaminated with hydrocarbons and other chemicals by filtering the pollutants from the water as it percolates through the soil and recharges the groundwater. During periods of little rain, baseflow forms the main flow of streams, and during summer it provides a cooling influence which "can be critical since cold water holds more oxygen." So, altogether rain gardens make for better surface water quality, groundwater quality, and overall hydrological health (Cozzetto 2001).

5.1 *Design of Rain Gardens*

Rain gardens can play an important role in improving the quality and reducing the quantity of stormwater runoff. While one rain garden may seem to provide little improvement in stormwater management, a collection of rain gardens can substantially benefit the environment. Homeowners can contribute to these benefits by making their own rain gardens. The advantages will not only improve the environment but will also enhance the beauty of yards and neighborhoods. This is because rain gardens are planted with wild flowers and native water tolerant and aquatic plants that can soak up the rain, filter pollutants, and provide valuable habitat for birds, butterflies, and other. Below are general guidelines for constructing rain gardens adapted from West Michigan Environmental Action Council (2002).

Evaluate the Soil

The first step in planning a rain garden is to examine the native soil. The soil should be able to absorb water draining from the property. Clayey soils have low permeabilities and tend to become waterlogged. If the site is predominantly clay it is recommended that the clay be removed and replaced with a more conductive soil. On the other hand, sandy soils drain well and may only require the addition of compost to loosen then and prepare them for gardening.
The soil infiltration rate can be tested by digging an 8 inch wide hole with a depth of 8 inches and pouring a bucket of water into it to see how long it takes to be absorbed. The standard infiltration rate should be one inch per hour (1 in/hr) and if it takes the water longer to be absorbed then the soil needs to be amended. It is recommended that soil replacement be a mix of about 50-60% sand, 20-30% topsoil, and 20-30% compost. This mix allows water to be absorbed while it supports the growth of healthy plants. It is important to make sure that no clay is in the replacement.

Siting the Rain Garden

The rain garden should be located at least 10 feet from the house to avoid infiltrating water from seeping into the foundation. Additional care should be taken so that the rain garden is not placed over a septic system. Rain gardens should also be placed on a gentle slope that catches downspout runoff.

Design of Pond Area

A dip must be created in the middle of the hole where water will collect as it is absorbed by the soil. The bottom of the garden should be kept flat to maximize storage capacity. The standard depth of a rain garden is about 6 inches but if the soil has very poor infiltration capacity, the depression should be shallower to reduce the water that gets trapped there. Alternatively, if the soil has high drainage the depression should be deeper so that storage capacity is increased.

Soil Testing

The pH of the soil is an important indicator of the type of plants the garden will support. It is recommended that the soil be tested to find out if any improvement is needed.

Planting the Garden

When it comes to picking plants, native species are recommended for cultivation as they can adapt to the local climate and can thrive with minimum maintenance. Some considerations that need to be taken into account when selecting plant species include: choosing the right plants for the particular climate and insolation patterns, taking into account the extent to which a plant will grow and how it will affect the view of the driveway for instance, and choosing plants that are beautiful and actually present an improvement to the landscape..

Rain Garden Care

Although rain gardens need little maintenance, they still require some minimum work to ensure they continue functioning properly. For instance, if it does not rain the plants should be watered. Watering is needed because during the period between planting and growth of root system, the newly planted species can not tolerate and survive a drought. Additionally, the area where water flows into the garden should have some physical barriers that will break the force of the flow during storms and thus prevent erosion of soil, mulch, and plants. Mulch should also be added in the spring or on any bare area to keep the garden moist and sponge like, ready to absorb rain. This will also prevent a hardpan from developing on the surface. As with any garden, weeding should be carried out regularly to avoid the growth of invasive plants. The garden should not be parked or driven on to avoid compaction of the soil and subsequent poor drainage.

5.2 *Modeling Flow in Rain Gardens*

Rain gardens are shallow depressions that allow stormwater runoff to infiltrate and recharge the groundwater, filtering pollutants in the process. The water flow through rain gardens has not been quantified and the quantity of storage in the subsurface and the above-ground soil has never been modeled. This presented a problem for modeling the rain garden in P8 since there is lack of data on its performance and in particular on water balance. Literature review revealed a solid technical paper by Dussaillant et al. (2004) on infiltration of stormwater in a rain garden which is summarized below:

5.2.2 Summary of Dussaillant's Research

Tools for modeling unsaturated flow that couple surface and subsurface flow are available. Tools that use Richards Equation to model infiltration and redistribution into layered soils are also available. There are no tools, however, that have capabilities to model both processes which are required for rain garden simulation. Dussaillant et al. (2004) developed a model called RECHARGE which is based on Richards Equation and couples surface ponding and soil-water flow in a rain garden with layered soil. They validated their model using an experimental rain garden with an area of 5.4 m^2 in Madison, Wisconsin. The rain garden had two valves that connected it to runoff from two roofs with an area of 50-60 m^2 each. The garden is essentially a lysimeter containing 6.5 m^3 of soil enclosed in a polyethylene liner which hydraulically isolates the garden soil allowing the measurement of water that percolates and exits by a bottom drain. The root zone is 50 cm deep, consisting of 60% mason's sand and 40% organic matter. Figure 11 shows the cross-sectional diagram of an experimental rain garden with lysimeters (Dussaillant et al. 2004). The storage zone lies beneath the root zone, consists of sand and is 70 cm deep. Rainfall was measured by a tipping bucket and roof rainfall by a trapezoidal flume. The soil water storage term was estimated using time domain reflectometry (TDR) probes placed at seven depths. The seepage through the soil was directed to a drain at the bottom of the lysimeter connected to a 100-meter long PVC pipe that emptied to a tank. Three controlled experiments were performed, where the water input was maintained until the rain garden ponded to 15 cm. Each of the experiments had different antecedent moisture conditions. In the first set-up the rain garden was very wet due to ponding the day before (VW experiment) and the second set-up had moderately wet initial conditions because two days had passed without any water input (MW experiment). Finally, the last set-up consisted of a garden which had not been watered for the past three days which brought the soil to field capacity (FC experiment). Average flow was about 7 gpm. According to the results obtained from the controlled experiments the model was seen to mimic the ponding times between experimental parameters and results obtained by model simulations reasonably well. The results suggested that rain gardens reach saturation very quickly, within an hour or two, and they provide both above-ground and subsurface storage.

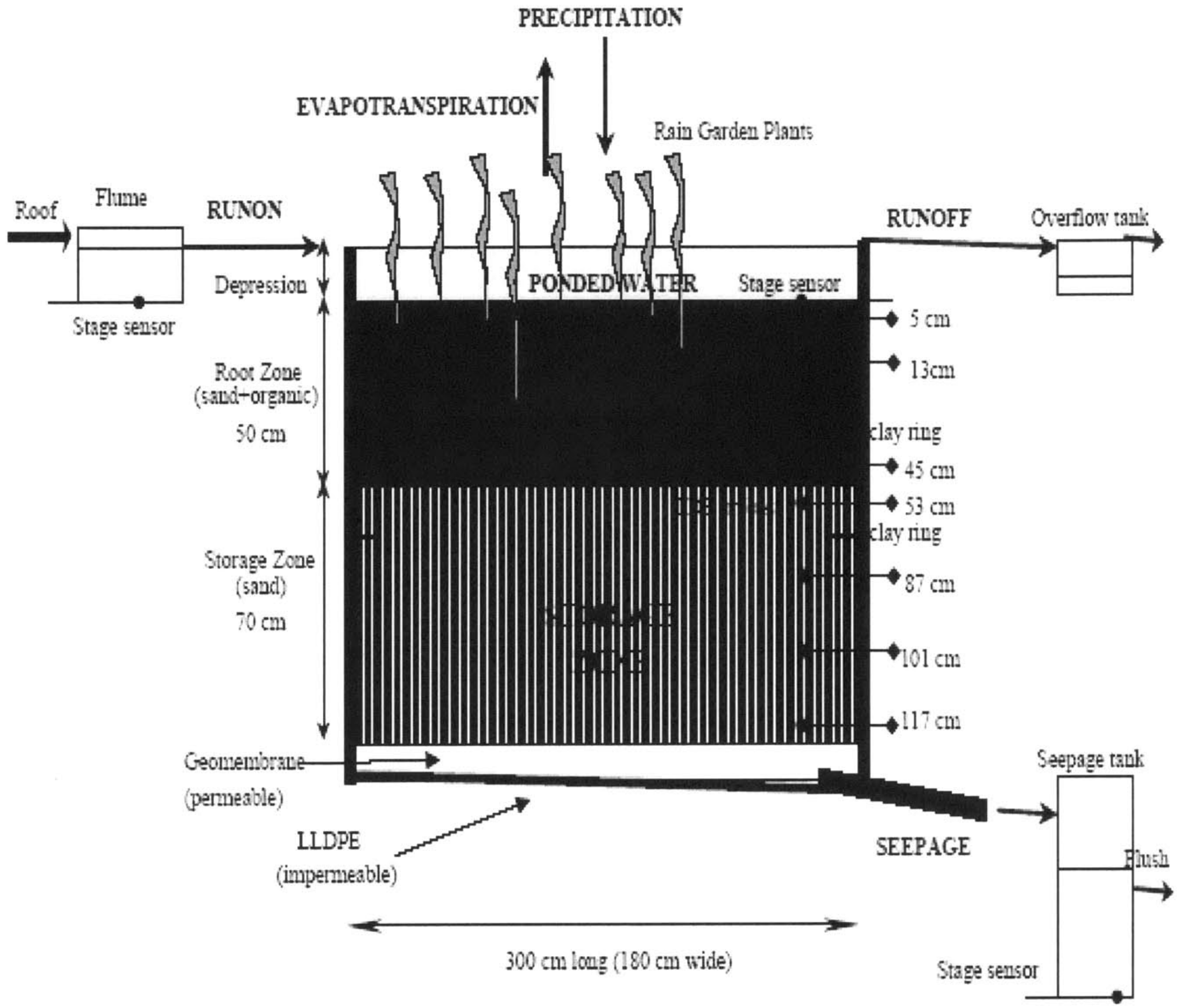

Figure 11:Cross section diagram of experimental rain garden lysimeter

5.2.3 Modeling a Rain Garden as a Device in P8

The assumption was made that rain gardens reach saturation very quickly and provide both above-ground and subsurface storage. We encountered difficulty in choosing a single P8 device for simulating them was encountered. As a result, a scheme that would "trick" P8 into simulating rain gardens was formulated. The approach taken was to model the above-ground storage as a detention pond (P8 device 1) and to model the subsurface part as an infiltration basin (P8 device 2). A schematic of the rain garden model in P8 is illustrated in Figure 12. The detention pond was modeled to have a permanent pool of zero volume and a flood pool equal to the above-ground storage volume in the rain garden. After the above-ground storage volume of the detention pond had been filled, the surface overflow was directed via a spillway outlet to the next downstream surface-water device. The infiltration from the detention pond was directed to the infiltration basin device via the flow splitter (P8 device 6). The flow splitter was placed between the detention pond and infiltration basin and tied to the surface elevation of the rain garden. Once the subsurface part of the rain garden (i.e. infiltration basin) was filled the flow splitter would direct any excess flow to the next device downstream.

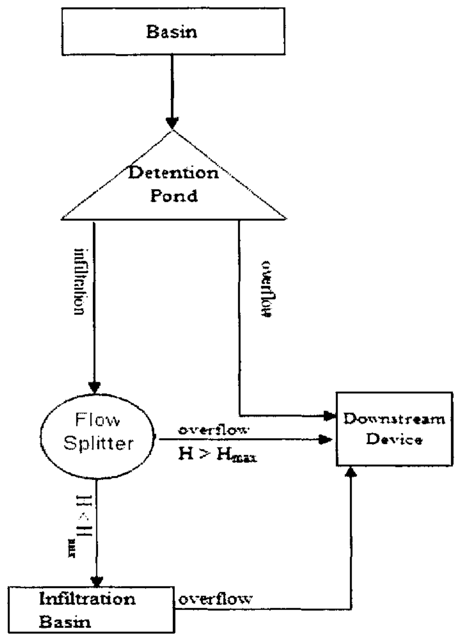

Figure 12: Schematic of a rain garden

6 The Nashoba Brook Watershed Model

Nashoba Brook is a tributary watershed of the SuAsCo watershed. SuAsCo stands for the Sudbury, Assabet, and Concord Rivers (see Figure 13). The watershed is a 377-square mile area encompassing, partially or wholly, 36 Massachusetts towns (see Figure 14). Acton, Carlisle, Framingham, Hudson, Marlborough, Maynard, Northborough, Southborough, Stow, and Sudbury all lie completely within the watershed. The SuAsCo Watershed is rapidly growing and developing and faces severe resource challenges. Many stretches of the Sudbury, Assabet, and Concord Rivers routinely fail their water quality standard for nutrient enrichment and experience both severe flooding and low flow concerns. The rivers' assimilative capacity to handle nutrients is severely stressed by non-point sources (stormwater) and wastewater treatment plant discharges. Throughout much of the Sudbury River downstream into the Concord River, fish consumption is banned due to mercury-laden sediments from the Nyanza Superfund Site. Invasive aquatic plant species compromise the river habitat for native species, and impair the recreational experience for boaters and anglers (SuAsCo).

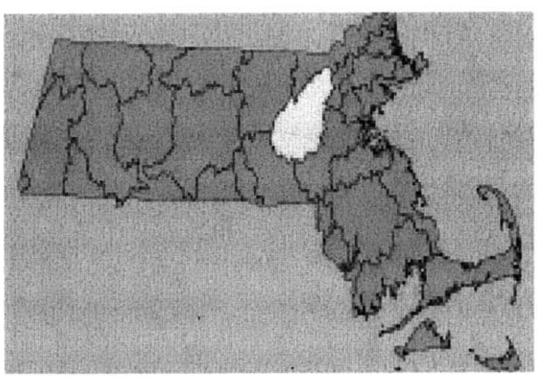

Figure 13: SuAsCo Watershed (SuAsCo)

(See Figure 15)

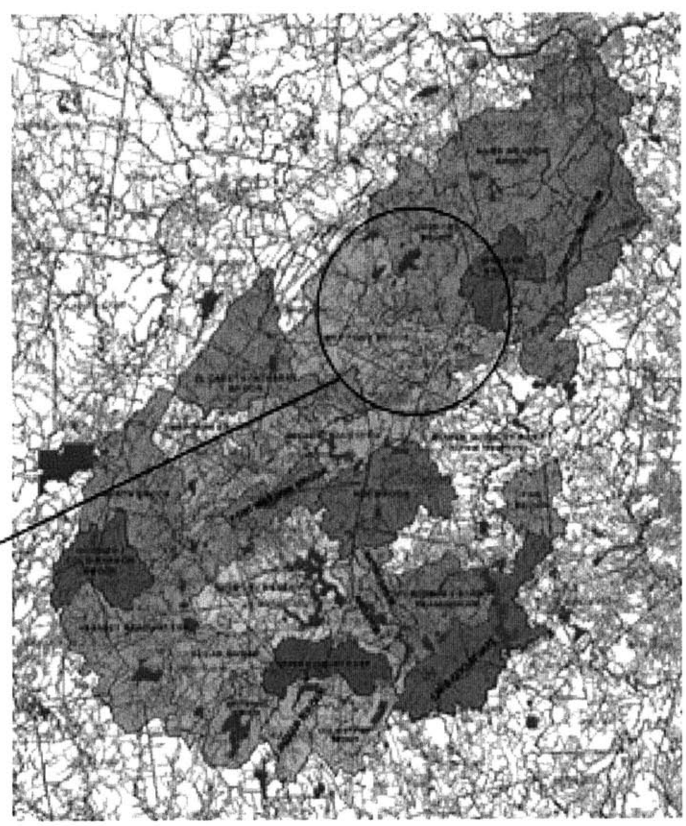

Figure 14: SuAsCo Tributary Watersheds (Fleming)

The town of Acton is divided into two major watersheds: Nashoba Brook and Fort Pond Brook (Woodard and Curran 2003). The Nashoba Brook watershed model was created under the assumption that a percentage of total residential landuse had rain gardens constructed to manage part of the stormwater runoff on-site. The effectiveness of rain gardens at improving water quality was then determined by looking at total phosphorus loadings predicted by the program, before and after the implementation of the devices.

6.1 *Nashoba Brook Properties*

The first step in the Nashoba Brook model development was to import a map of the SuAsCo watershed from the Massachusetts Geographic Information System (GIS) website. The area of the SuAsCo watershed circled in Figure 14 above was also imported along with its land use map (see Figure 15). A table of the properties of all land use types which included areas was exported from ArcMap to an excel spreadsheet. The table was then sorted out according to landuse and a curve number (CN) was designated to each area. The hydrologic soil group for the area was assumed to be in between soil groups B and C

Figure 15: The Nashoba Brook Landuse Map

A weighted curve number of 71 was determined for the watershed and detailed calculations are shown in Appendix A.

The next step involved calculating the time of concentration. The time of concentration, t_c, is the time it would take the hydraulically most distant drop of water in a watershed to travel to the outlet. Water flow in a watershed is divided into three components: overland flow, shallow concentrated flow, and channel flow. For modeling purposes, the time of concentrations for overland and shallow concentrated flow were lumped and a separate t_c for channel flow was calculated as shown in Figure 16.

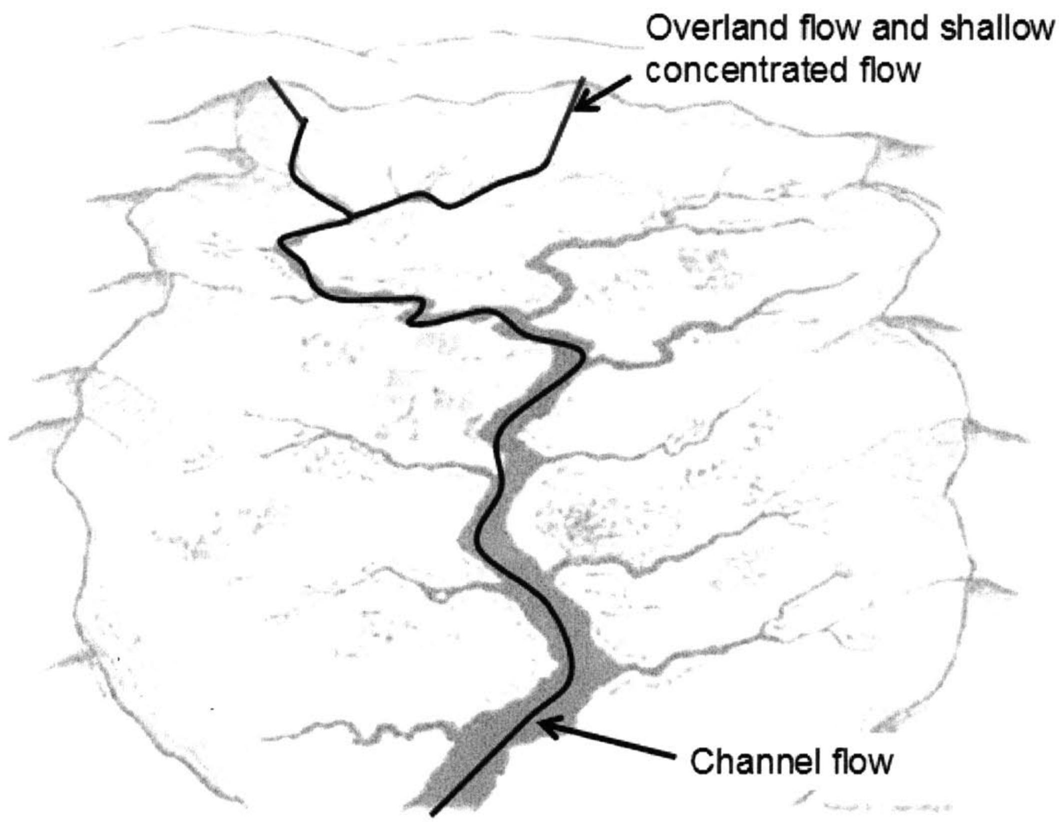

Figure 16: Time of Concentration (RiverSmart)

The procedure involved determining the height of the most remote point above the outlet and the maximum length of travel for each type of flow. The values were then plotted on a nomograph based on a study by Kirpich (1940) and this gave the time of concentration. An example is shown in Figure 17.

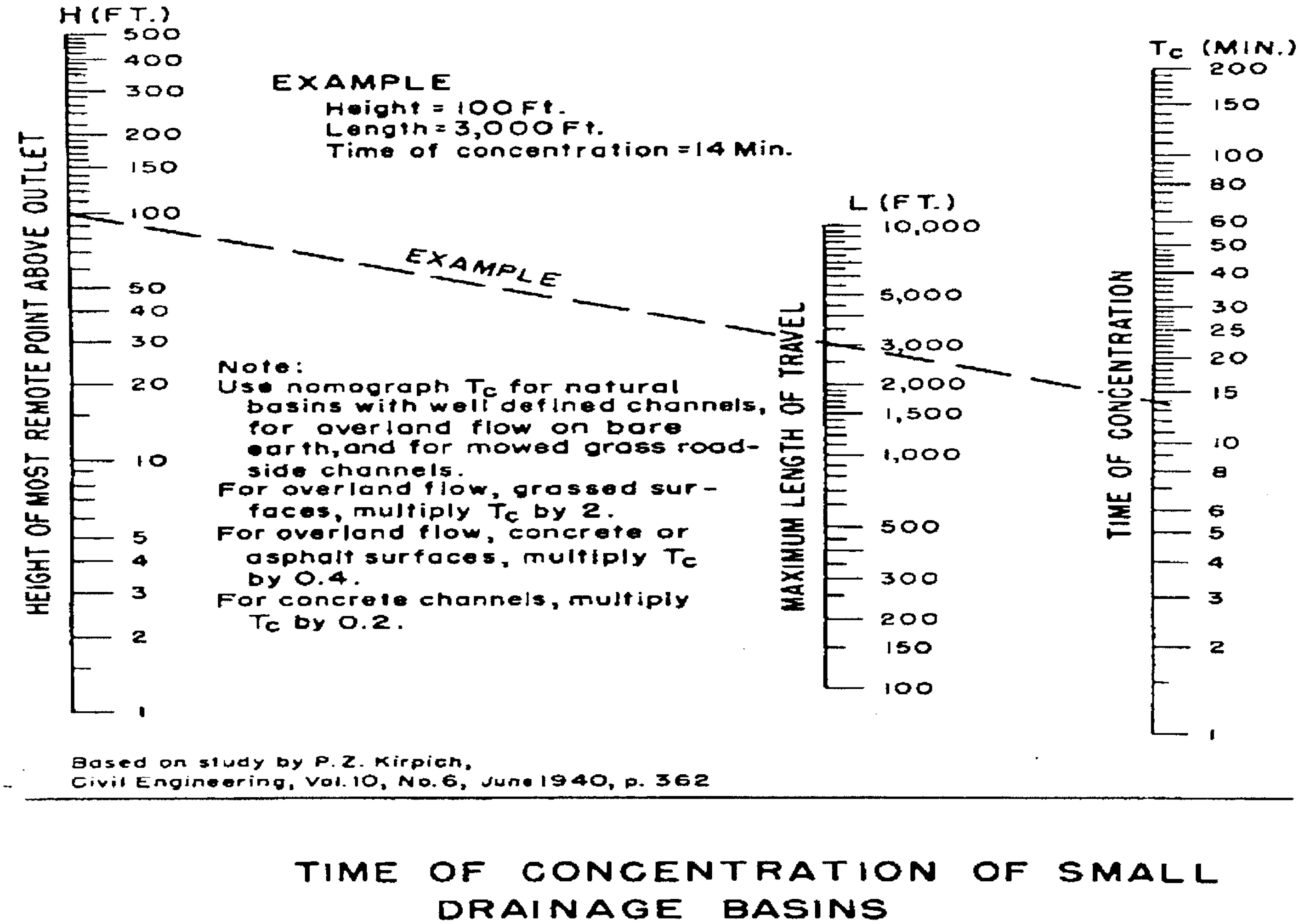

Figure 17: Calculation of T_c using Nomograph (Kirpich 1940)

The elevation drop for overland and shallow concentrated flow was determined to be 29 feet and the travel distance to the head of the channel was 3,065 feet. Plotting the two values on the nomograph in Figure 17 yielded an approximate t_c of 25 minutes. This value was multiplied by two to account for roughness and this resulted in a t_c of 50 minutes. Similarly, using an elevation drop of 118 feet and a travel length of 32,000 feet the time of concentration for channel flow was determined to be 50 minutes. The sum of both times of concentration, t_c = 100 hours, was used in P8.

6.2 *The Nashoba Brook P8 Model*

Three scenarios were created to model the effectiveness of rain gardens if implemented on residential properties in the Nashoba Brook watershed. The cases tested assumed that 25, 50, and 75 percent of total residential landuse employed rain gardens to manage their stormwater on-site. The rain gardens were assumed to occupy 10% of the total residential areas. The general P8 flow schematic for all three cases is illustrated in Figure 18. The only parameter that changed was the total area of the rain garden which depended on the percent of residential areas modeled. The surface runoff from the watershed was assumed to first flow to the rain garden and when the rain garden reached it's total storage capacity, the overflow was directed to a pipe/manhole as would be done conventionally. Any infiltration was directed to an aquifer.

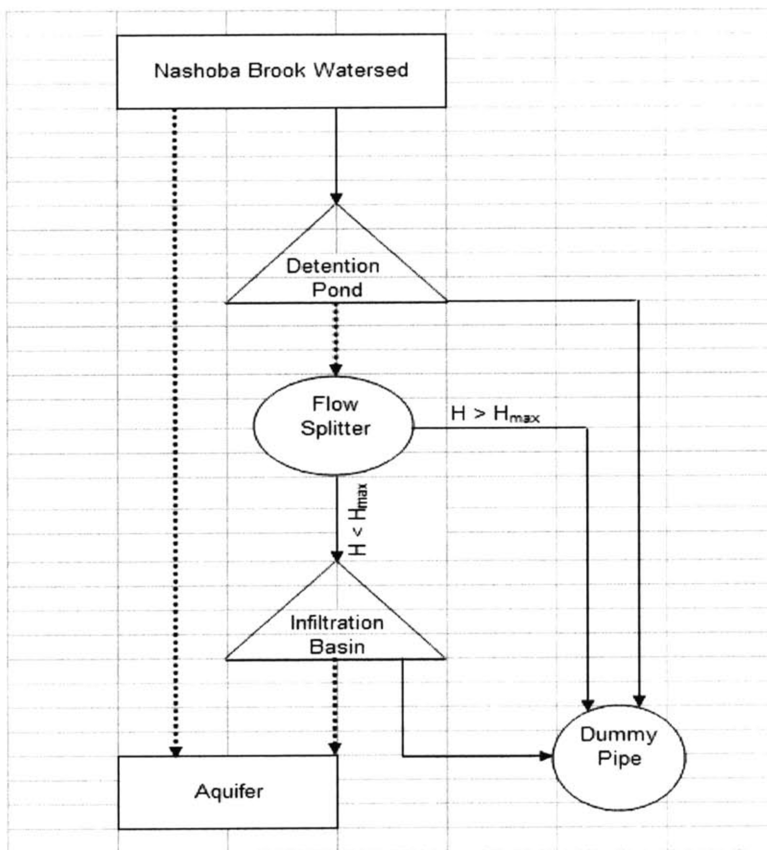

Figure 18: Nashoba Brook P8 Network

6.3 *P8 Results*

The P8 results indicate increasing total phosphorus removal efficiency with increasing percentage of rain gardens used. The predicted removal efficiencies are approximately 55%, 70%, and 75% for 25%, 50%, and 75% rain garden use respectively, as is illustrated in Figure 19.

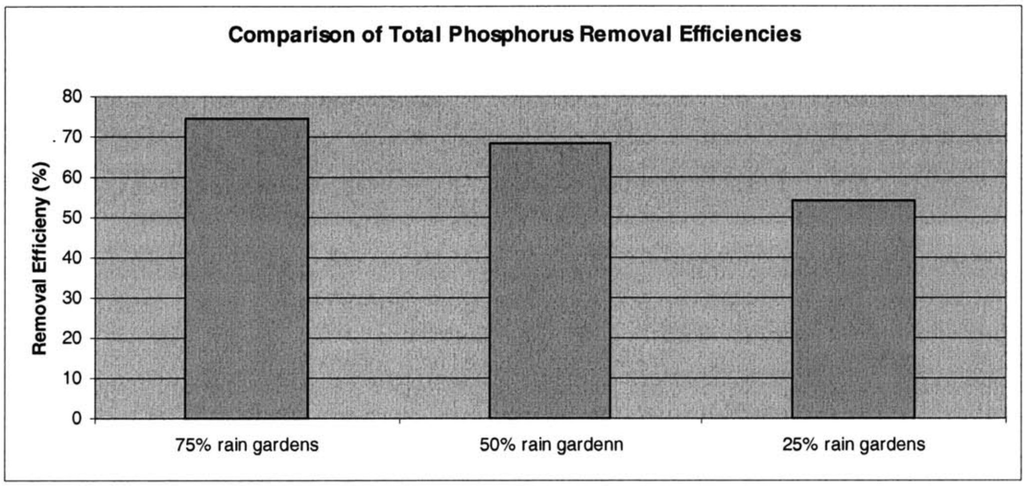

Figure 19: Comparison of total phosphorus removal efficiencies

A comparison of total phosphorus loading in the outflow shows significant reduction by any amount of rain gardens. This is illustrated in Figure 20.

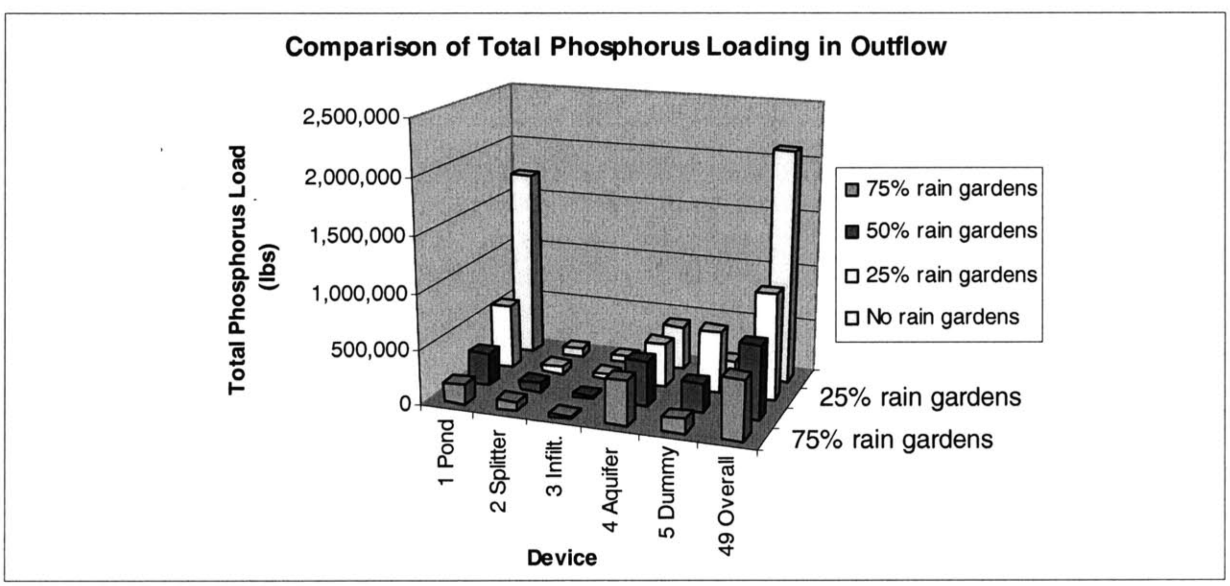

Figure 20: Comparison of total phosphorus loading in outflow

From the figure above one can see that the TP loading before any rain gardens are used is 2,110,000 pounds. The TP loadings are 965,000 lbs, 662,000 lbs, and 531,000 lbs for 25%, 50%, and 75% rain gardens respectively. These results are strongly in favor of rain gardens.

It should be noted that the analyses do not generate absolute values but provide relative values for comparison. This model can serve as a preliminary tool for assessing the feasibility and effectiveness of using rain gardens on residential properties.

7 The Discovery Museums' Case Study

In the Fall of 2004, The Discovery Museums (TDM) expressed a desire to turn their west parking lot into a green space and expand their east parking lot (see Figure 21). As a result of the proposed construction TDM face the necessity to formally manage their stormwater runoff. As a result a case study was created by the MEng group project to determine the feasibility of implementing LID on the museum site. The project goal was to increase parking capacity, enhance aquifer recharge, and improve runoff water quality. The water quality modeling of the project examined the use of rain gardens and infiltration basins to minimize the contribution of total phosphorus load from non-point sources. Since runoff from small urban developments eventually discharges into the Assabet River Basin, improved water quality of the runoff is directly related to improved water quality of the river.

7.1 *Background*

The Discovery Museums are located in Acton, Massachusetts, about 25 miles west of Boston. The town of Acton is part of the Assabet River watershed and derives its drinking water supply solely from groundwater. Over the years, increased land development has resulted in the creation of impervious areas which have decreased the amount of water that infiltrates and replenishes groundwater. Reduced infiltration compounded by groundwater extraction has diminished the base flow to the Assabet River. This has exacerbated the water quality because there is less inflow to dilute the pollutants (Brown et al. 2005).

Currently, stormwater runoff from the west parking lot drains offsite to the adjacent road (Main Street) through catch basins and the driveway. Runoff from the east parking lot drains to the neighboring conservation area as shown in Figure 21.

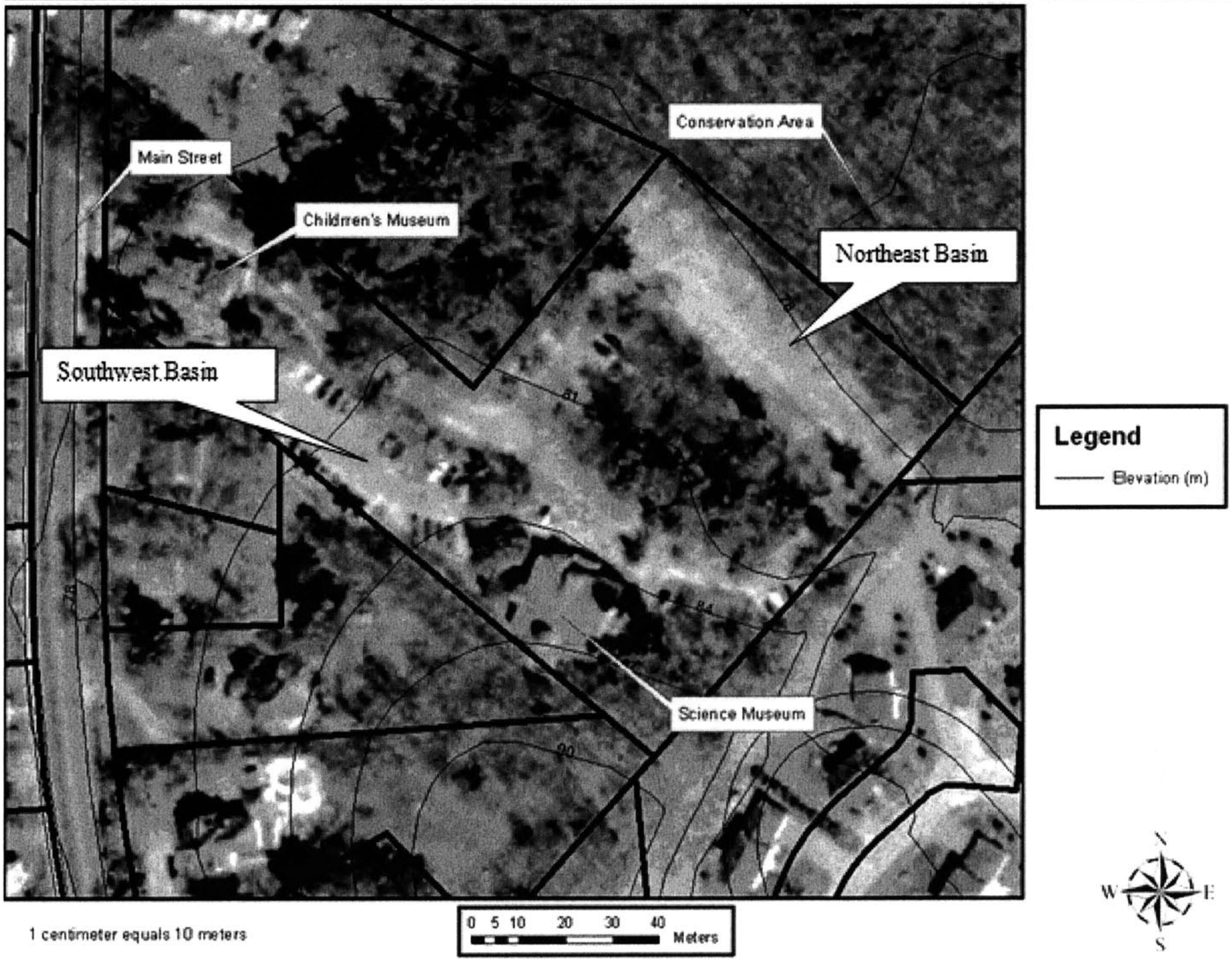

Figure 21: The Discovery Museums' Current Layout (Brown et al. 2005)

7.2 *P8 Model Development*

Three models of the site were developed that mimicked pre-development, current, and proposed site conditions. Hourly rainfall and daily temperature data for the National Weather Service weather station at Worcester Airport were used. Data span the period from 1948 to the present. From this record, a three-decade period from 1960 to 1996 was selected as representative for purposes of simulation. Particle data from the NURP 50th percentile (Athayde et al. 1983) were used. The sizes of the devices used were based on the hydrologic modeling and water quality was analyzed to determine if any improvement occurred. The models of all three levels of site development are described below.

7.2.2 Pre-Development Site Model

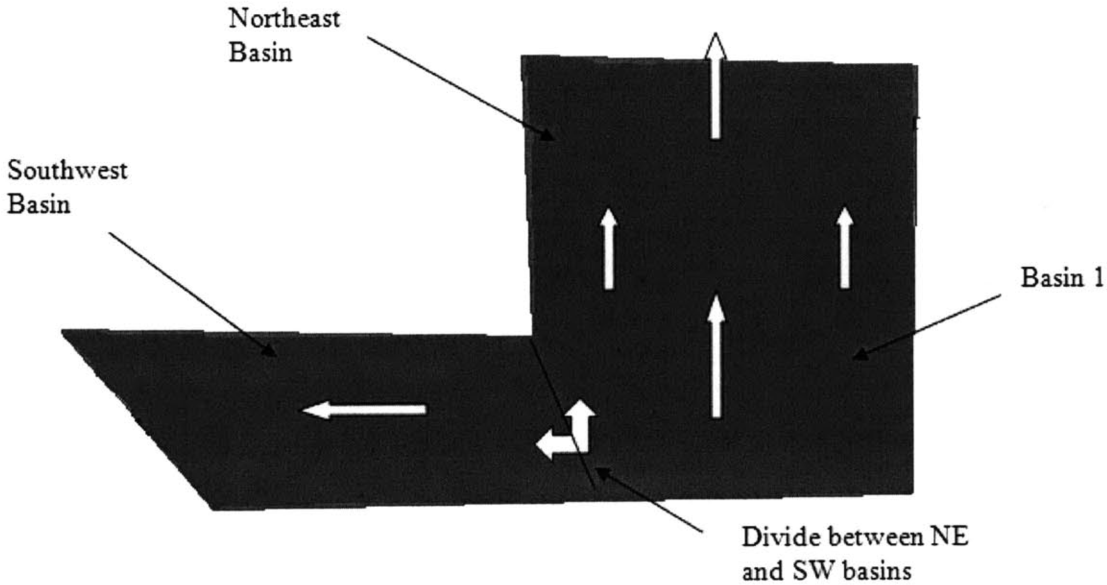

Figure 22: Pre-development site layout

The Northeast basin was modeled in P8 using the configuration depicted in Figure 22. The flow paths are depicted by the white arrows. The total area contributing to the flow is the entire forested area which was modeled as basin 1. The amount of precipitation that infiltrates into the ground and recharges the aquifer is determined in the program by specifying a curve number. The Natural Resources Conservation Service method was used to determine the hydrologic soil group curve number for good woods which was 73. Any overland flow from the site ends up in the conservation area but for modeling purposes and water balance calculations, surface runoff was routed to a dummy pipe as illustrated in the schematic below (Figure 23).

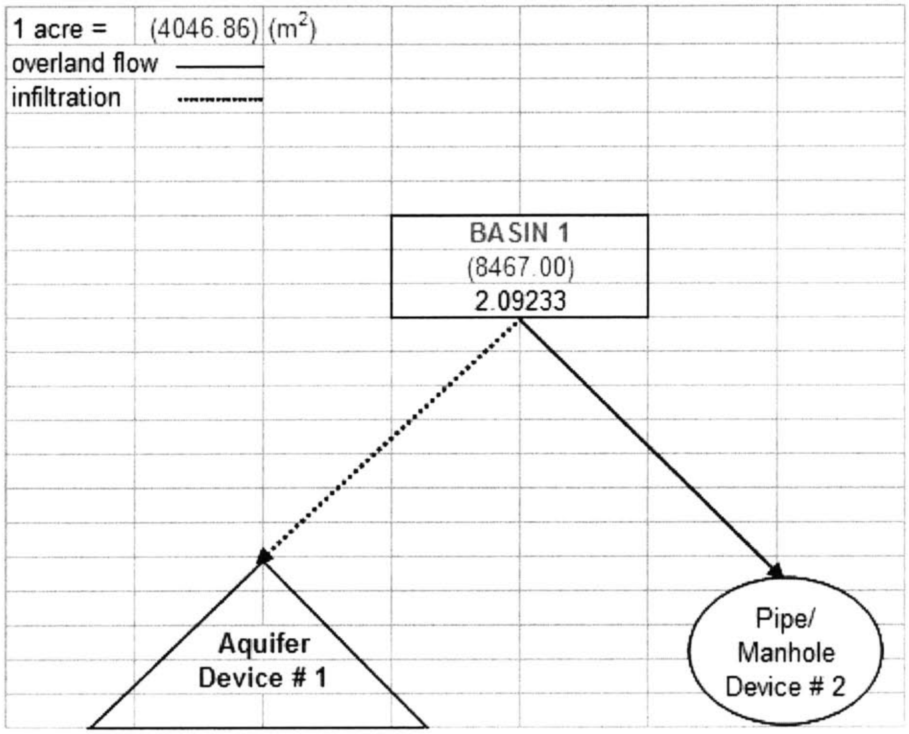

Figure 23: Pre-developed site P8 network

7.2.3 Current Site Model

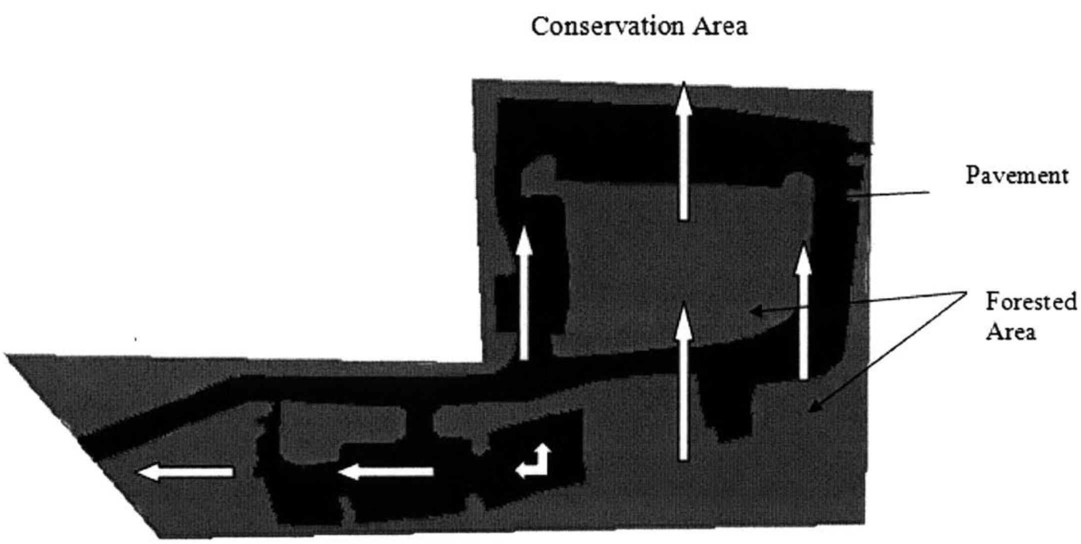

Figure 24: Current site layout

Figure 24 shows how the current northeast basin of the site is divided into paved and forested areas. The schematic of flow routing is similar to the pre-development flow path (see Figure 25). The model inputs differ however since the curve number has increased due to the impervious pavement. In order to model this mixed surface cover a weighted average for the curve number was developed based on the calculations shown in Appendix C.

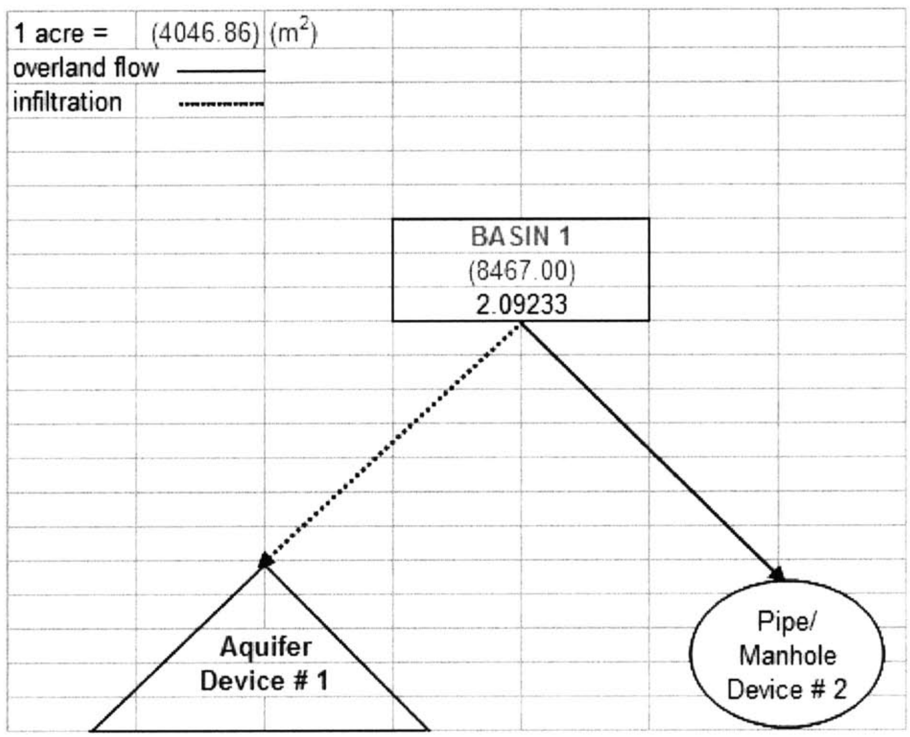

Figure 25: Current site P8 network

7.2.4 Proposed Site Model

Figure 26: Proposed site layout

shows the new site layout with increased parking capacity and the addition of LID technologies. There are three LID devices used: the infiltration basin which is labeled as device # 1, and the two rain gardens which are labeled as device #2 and device #3. For modeling purposes, the areas contributing to flow were divided into six basins and are labeled below.

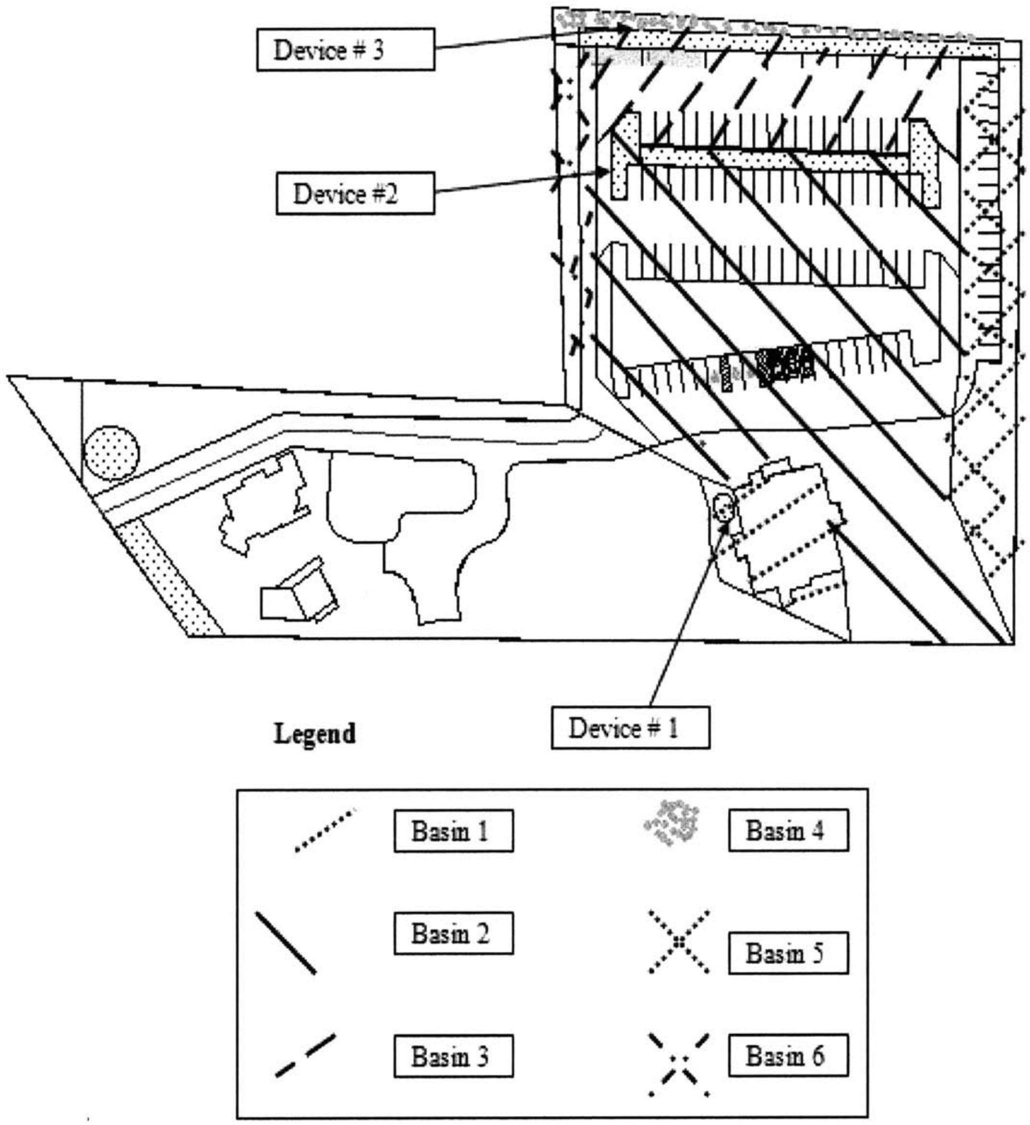

Figure 26: Proposed site layout

Each basin is comprised of one or more sub-basins, the flow lines of which enter a common device. Figure 27 illustrates how each basin is sub-divided into one or more sub-basins. Table 3 describes the sub-basins within each basin, and Table 4 gives a summary of the area and weighted curve number of each basin. The rain gardens' above-ground storage will be created by replacing the existing silt loam with a mixture of soil containing primarily sand with an effective infiltration rate of 6 inches per hour. The above-ground storage was assumed to have a maximum storage capacity of 0.15 m and the subsurface storage a maximum head of 1m. More details can be found in Appendix C.

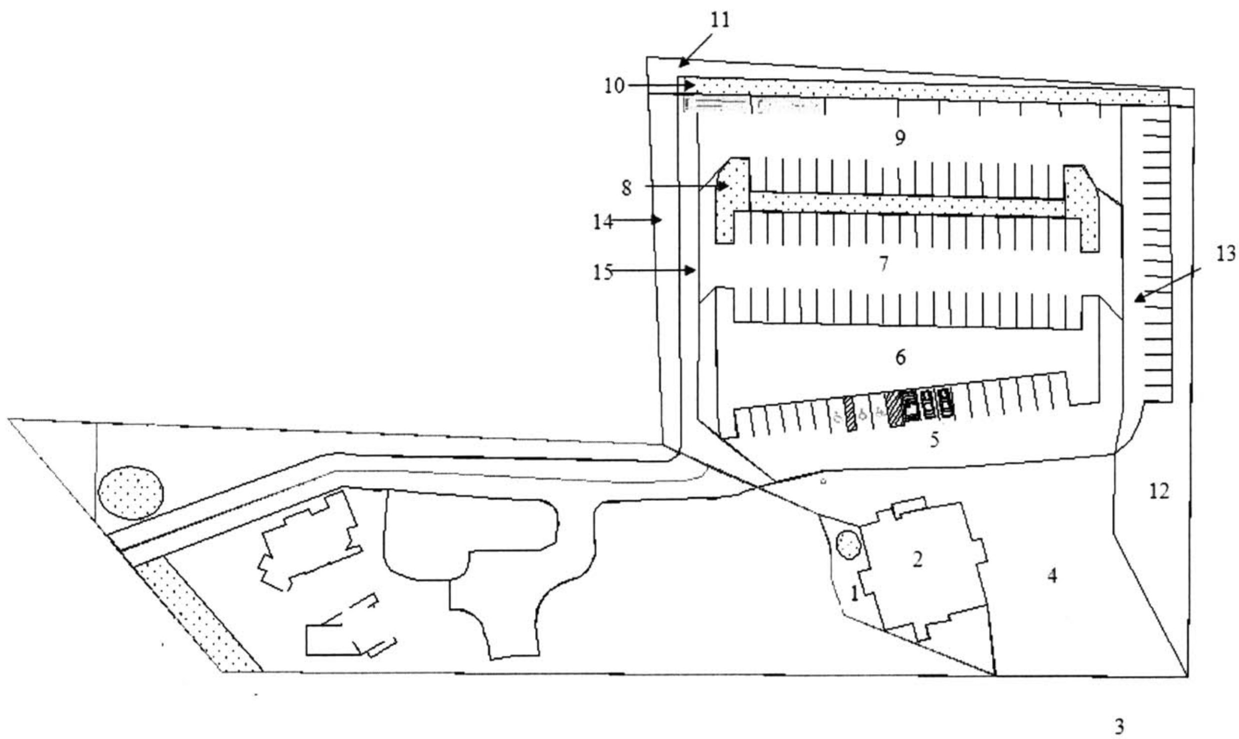

Figure 27: Sub-basins of the proposed site layout

Table 3: Description of each sub-basin

Sub-basin	***Description***
1	Forested area in the vicinity of the museum; within basin 1
2	Impervious area occupied by the museum building; within basin 1
3	Hills behind the museum; part of basin 2
4	Forested area around the museum; within basin 2
5	Parking lot pavement closest to museum; part of basin 2
6	Grass island between the first two rows of parking spaces; part of basin 2
7	Parking lot pavement between grass island 6 and the first rain garden (device # 2); part of basin 2
8	Contributory area of rain garden 1 (device # 2), part of basin 2
9	Parking lot pavement between rain gardens 1 (device # 2) and 2 (device # 3); part of basin 3
10	Contributory area of rain garden 2 (device # 3); part of basin 3
11	Small forested area downstream of rain garden 2, basin 4
12	Forested area in basin 5
13	Paved area in basin 5
14	Forested area in basin 6
15	Paved area in basin 6

Table 4: Summary of basin properties

	Area (m^2)	Area (ac.)	Weighted CN
BASIN 1	532	0.13	90
BASIN 2	4960	1.23	84
BASIN 3	1290	0.32	94
BASIN 4	196	0.05	73
BASIN 5	989	0.24	83
BASIN 6	484	0.12	86

After assigning a curve number and area for each basin, the network in Figure 28 was created to show the general flow paths and linkages between the watersheds and devices. The devices that make up rain gardens 1 and 2 are also labeled.

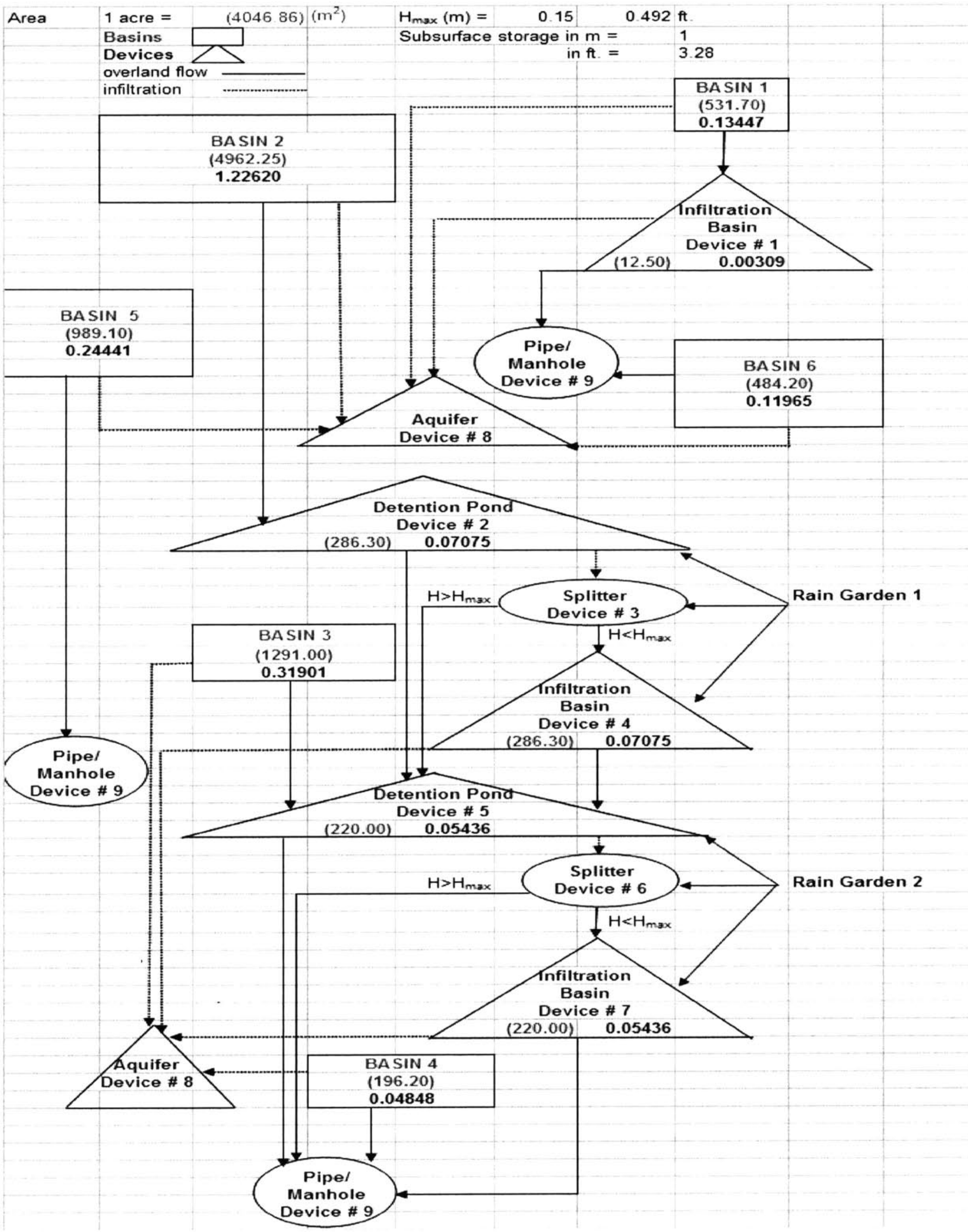

Figure 28: Proposed site P8 network

7.3 *Results and Conclusion*

Since no devices capable of treating or filtering pollutants were present in the pre-developed and current site conditions the total phosphorus inflow and outflow from each basin are equal. However, the total phosphorus (TP) load in the outflow from each basin differs since the current site has been developed and more sources of phosphorus, such as fertilizer, are present. The overall TP loads are approximately 34pounds and 64 pounds for the pre-developed site and the current site, respectively. A plot comparing the outflow loads from both site configurations is shown in Figure 29 below. The significant increase in TP load demonstrates the impact of conventional stormwater management on water quality.

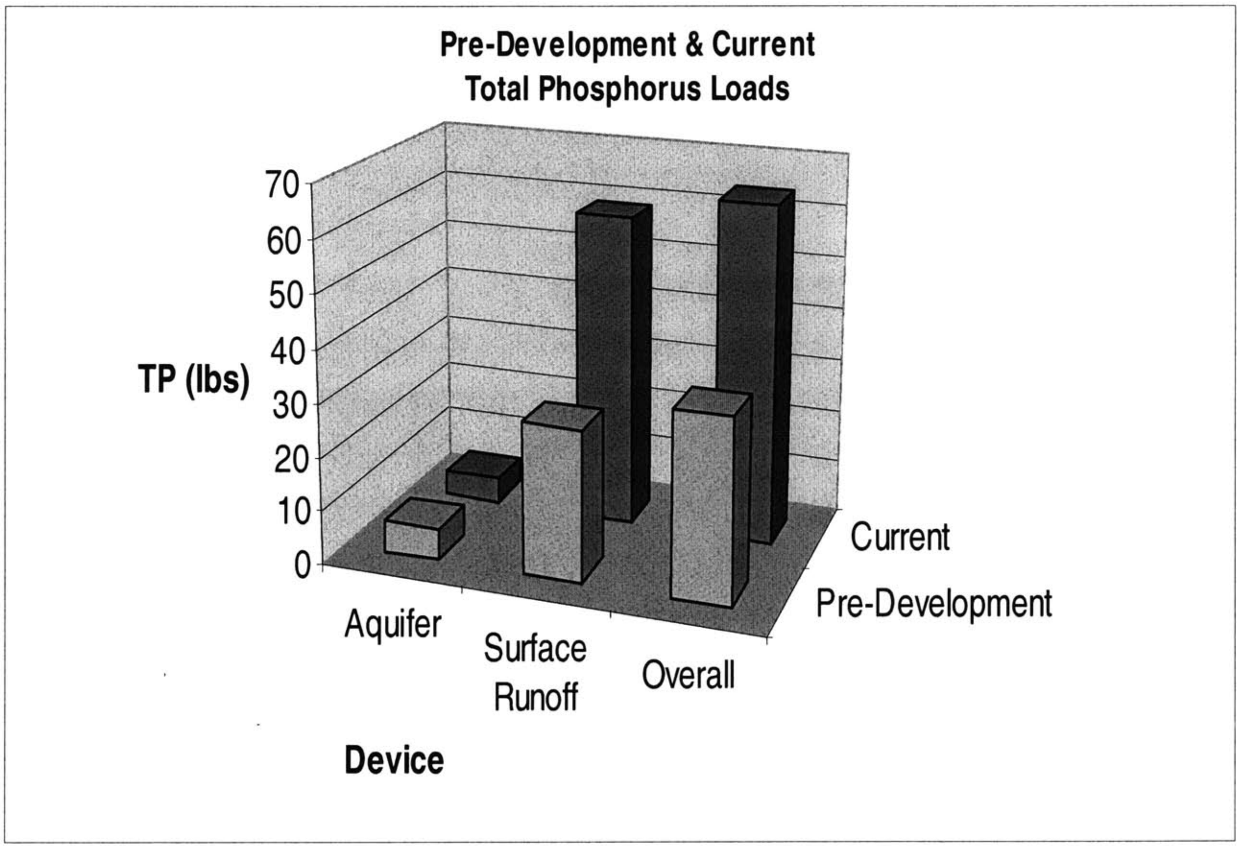

Figure 29: Plot of total phosphorus load in outflows from the pre-developed and current sites

In contrast to the pre-developed and current sites, the proposed site design uses three LID devices and a significant improvement in water quality between the inflow load and the outflow

TP loads is evident in Figure 30. The TP inflow load is 65 pounds and the outflow is 18 pounds which is equivalent to a removal efficiency of approximately 72%.

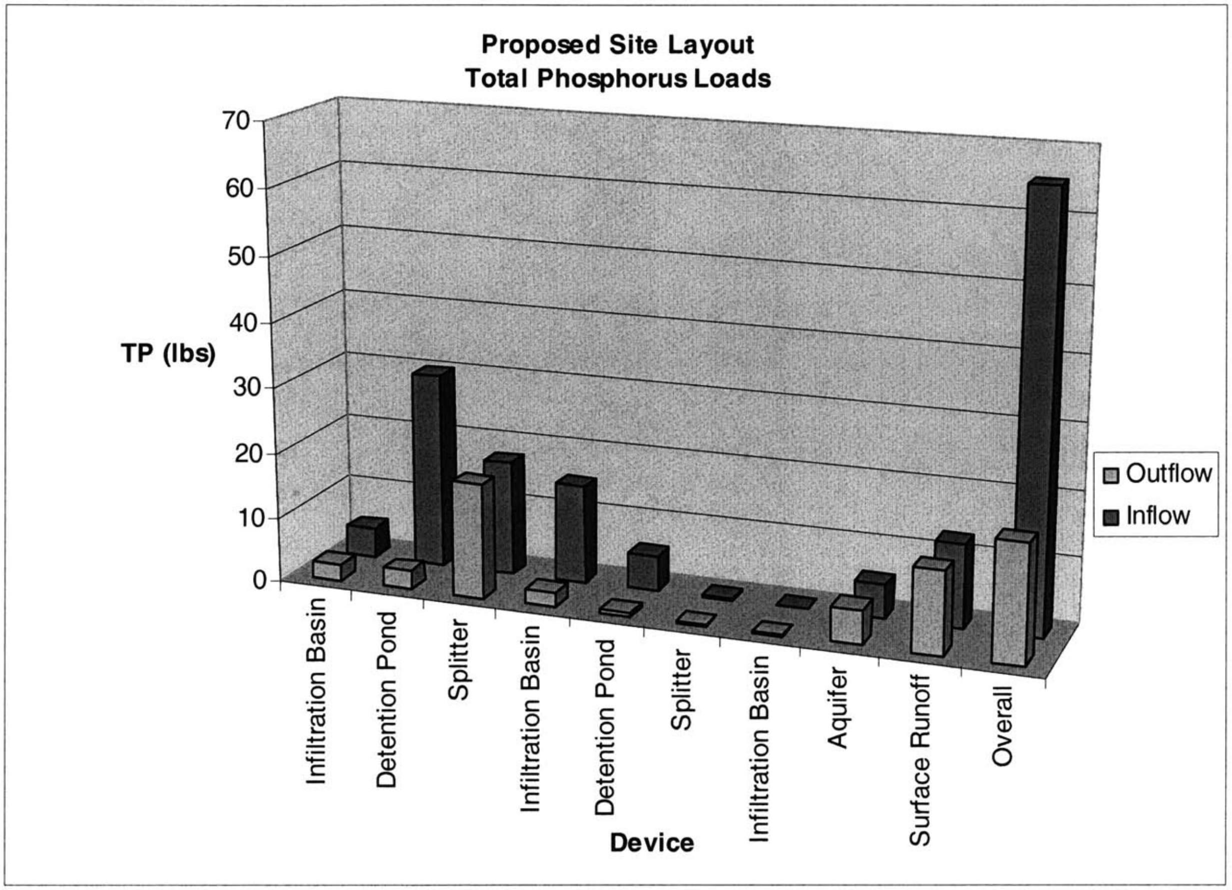

Figure 30: Comparison of TP loads between the proposed site inflows and outflows

The TP inflow to the pre-developed site is smaller than the inflows to the current and proposed site layout as is depicted in Figure 31. This difference in TP loads illustrates the impact of anthropogenic activities, such as land development and application of fertilizers, on water quality. A comparison between the outflow of all three site layouts shows that LID TP loading is 18 pounds which is much smaller than the 64 pound load due to conventional stormwater management on the current site (see Figure 32). The LID design also shows a significant improvement from the pre-development outflow load of 34 pounds which is due to the fact that rain gardens and infiltration basins have the ability to treat pollutants using a variety of methods which include filtration, settling, biological uptake, and chemical reactions.

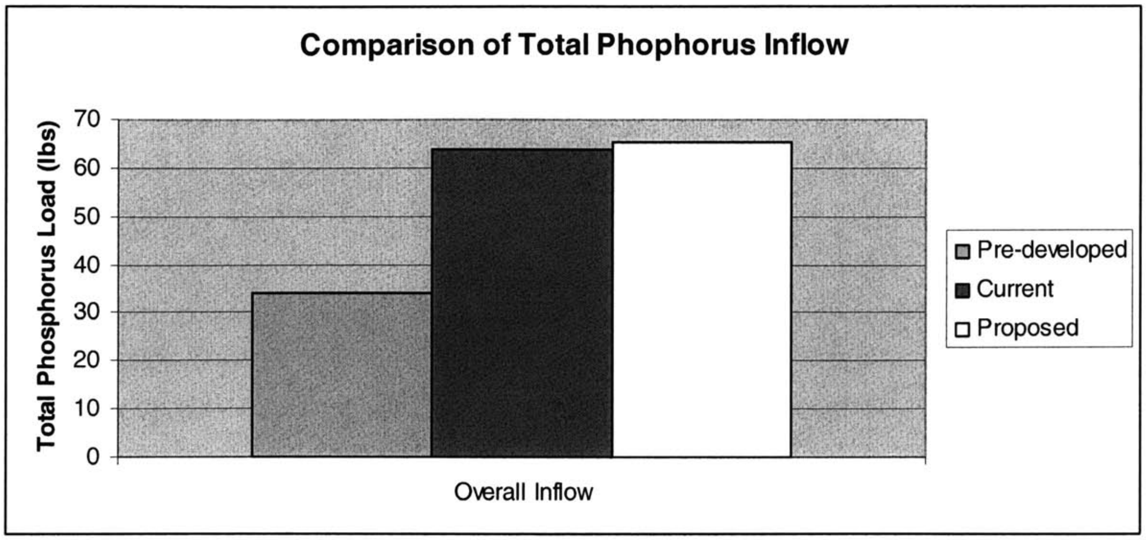

Figure 31: Comparison of TP inflows to each of the three site designs

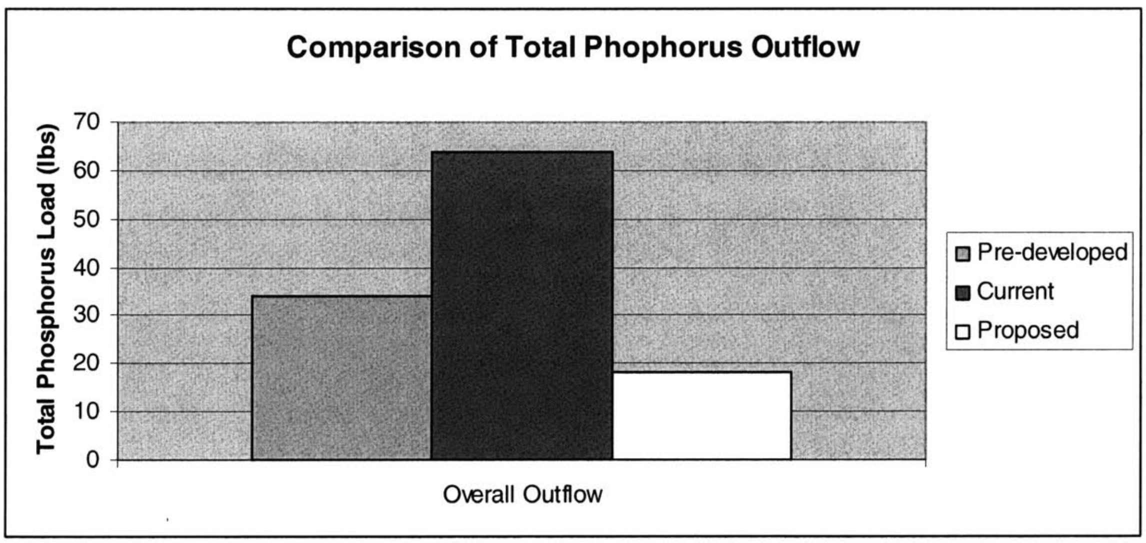

Figure 32: Comparison of TP outflows from each of the three site designs

8 Conclusion

The Assabet River is polluted with organic matter and nutrients such as phosphorus, and experiences low dissolved oxygen. The impairment is especially pronounced in the summer months when eutrophication most often occurs. Continuous water withdrawal in the Assabet River watershed and decreased aquifer recharge are significant contributors to the pollution problem. This results in decreased base flow to the Assabet River, thus increasing pollutant concentrations.

Another reason for the impairment and reduced aquifer recharge is due to conventional stormwater management. Conventional methods use impervious surfaces such as curbs, gutters, and catch basin to direct stormwater via storm drains and discharge into the receiving water body. The accelerated runoff washes off pollutants from the ground surface, such as phosphorus, and carries them to the river. Low impact development (LID) evolved to minimize the adverse effects of conventional stormwater management (Brown et al. 2005).

LID uses small, site level, landscape features such as ponds and vegetative biofilters to reduce the quantity and improve the quality of runoff. Of particular interest are the relatively new LID devices called rain gardens. These technologies are basically shallow depressions in the ground. They have the capacity to store stormwater both in the subsurface and above-ground. Additionally, they have the ability to filter pollutants as the runoff infiltrates in them (Brown et al. 2005).

In order to investigate the effectiveness of rain gardens and other LID technologies at improving phosphorus concentrations in stormwater runoff, two case studies were developed. The first case involved the implementation of rain gardens on different percentages of total residential land use in the Nashoba Brook watershed. Results indicate that rain gardens can significantly improve runoff water quality. The second case is part of the MEng group project for the Discovery Museums located in Acton, Massachusetts. The project involved the redesign of the northeast parking lot to increase its capacity and manage stormwater on-site. Infiltration basins and rain gardens were used as part of the new design. The runoff water quality was modeled for the pre-developed, current, and proposed site layout. The results also showed improved water quality. For both projects the P8 Urban Catchment model was used.

This thesis has raised my awareness of the environmental impacts associated with modernization and land development. I have realized that most environmental problems encountered in our modern society do not have simple solutions. They require the in-depth study of the multiple factors and processes that affect the ecosystem. I think that the most important approach to dealing with environmental issues is to be conscious of the problems and have the good will to tackle them in a scientific and responsible manner. This requires taking into consideration not only the short term effects, but also the long term impacts on the ecological balance, and the possibility of sustainable progress.

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Appendix A. The Nashoba Brook Case Study Calculations and P8 Inputs

Weighted Curve Number

LU21_CODE	Description	Imp. CN	% Imp	Perv. CN	% Perv	Weighted CN
10	Multi-family Residential	98	80	68	20	92
11	High-dednsity (<1/4 ac) Residential	98	57	68	43	85
12	Medium-density (1/4-1/2 ac) Residential	98	13	68	87	72
13	Low-density (>1/2 ac) Residential	98	10	68	90	71

LU21_CODE	Description	Area (m^2)	Area (ac.)	CN	Area*CN
1	Cropland	21,126,654	5221	83	433302
2	Pasture	3,092,531	764	74	56549
3	Forest	255,188,037	63058	66	4161850
4	Wetland	21,777,176	5381	98	527363
5	Mining	8,133,630	2010	85	170838
6	Open Land	6,731,540	1663	74	123092
7	Participation Recreation	100,286	25	74	1834
8	Spectator Recreation	2,467,350	610	x	0
10	Multi-family Residential	11,690,826	2889	92	265776
11	High-dednsity (<1/4 ac) Residential	273,433	68	85.1	5750
12	Medium-density (1/4-1/2 ac) Residential	66,917,426	16536	71.9	1188914
13	Low-density (>1/2 ac) Residential	106,275,434	26261	71	1864547
15	Commercial	13,815,566	3414	93	317493
16	Industrial	20,254,992	5005	90	450461
17	Urban Open	9,693,249	2395	74	177249
18	Transportation	4,646,989	1148	90	103347
19	Waste Disposal	824,540	204	74	15077
9 & 20	Water-based Recreation	9,405,864	2324	x	0
21	Woody Perennial	2,366,008	585	66	38587
	Totals		139,561		9902029
	Weighted Curve Number				**71**

Rain Garden Areas

LU21_CODE	Description	Area (ac.)
10	Multi-family Residential	2,889
11	High-dednsity (<1/4 ac) Residential	68
12	Medium-density (1/4-1/2 ac) Residential	16,536
13	Low-density (>1/2 ac) Residential	26,261
	Total Residential Area (ac.)	45,753

Percent of total residential areas with rain gardens	*Land Area (ac.)*
25%	11,438
50%	22,877
75%	34,315

% Residential Landuse with Rain Gardens	*Rain Garden Area (ac.)*
25%	1,144
50%	2,288
75%	3,431

Appendix B. The Nashoba Brook Case Study P8 Results

Inflows

25% rain gardens ASSABET1.CAS 1/3/1960 1/1/1996

variable = 7 total phosphorus
mass balance term = 09 total inflow

Device	volume (ac-ft)	load (lbs)	conc. (ppm)	removal (%)
1 Pond	3,299,710	1,710,729	0.191	65.64
2 Splitter	2,637,977	70,889	0.01	0
3 Infilt.	2,637,977	70,889	0.01	25.72
4 Aquifer	15,353,540	398,522	0.01	0
5 Dummy	2,544,394	566,434	0.082	0
49 Overall	17,897,930	2,107,225	0.043	54.15

50% rain gardens ASSABET2.CAS 1/3/1960 1/1/1996

variable = 7 total phosphorus
mass balance term = 09 total inflow

Device	volume (ac-ft)	load (lbs)	conc. (ppm)	removal (%)
1 Pond	3,299,710	1,710,729	0.191	82.54
2 Splitter	3,080,503	82,761	0.01	0
3 Infilt.	2,051,803	55,101	0.01	57
4 Aquifer	15,880,400	400,262	0.009	0
5 Dummy	1,999,185	262,226	0.048	0
49 Overall	17,879,600	2,107,501	0.043	68.49

75% rain gardens ASSABET3.CAS 1/3/1960 1/1/1996

variable = 7 total phosphorus
mass balance term = 09 total inflow

Device	volume (ac-ft)	load (lbs)	conc. (ppm)	removal (%)
1 Pond	3,299,710	1,710,729	0.191	89.66
2 Splitter	3,226,847	86,718	0.01	0
3 Infilt.	2,337,258	62,793	0.01	66.87
4 Aquifer	16,326,680	401,650	0.009	0
5 Dummy	1,562,168	129,056	0.03	0
49 Overall	17,888,860	2,107,714	0.043	74.77

Outflows

25% rain gardens ASSABET1.CAS 1/3/1960 1/1/1996

variable = 7 total phosphorus
mass balance term = 12 total outflow

Device	*volume (ac-ft)*	*load (lbs)*	*conc. (ppm)*	*removal (%)*
1 Pond	3,299,711	586,694	0.065	65.64
2 Splitter	2,637,977	70,889	0.01	0
3 Infilt.	2,637,960	52,655	0.007	25.72
4 Aquifer	15,353,540	398,522	0.01	0
5 Dummy	2,544,394	566,434	0.082	0
49 Overall	17,897,920	964,955	0.02	54.15

50% rain gardens ASSABET2.CAS 1/3/1960 1/1/1996

variable = 7 total phosphorus
mass balance term = 12 total outflow

Device	*volume (ac-ft)*	*load (lbs)*	*conc. (ppm)*	*removal (%)*
1 Pond	3,299,710	297,124	0.033	82.54
2 Splitter	3,080,504	82,761	0.01	0
3 Infilt.	2,051,775	23,693	0.004	57
4 Aquifer	15,880,420	400,262	0.009	0
5 Dummy	1,999,184	262,226	0.048	0
49 Overall	17,879,600	662,487	0.014	68.49

75% rain gardens ASSABET3.CAS 1/3/1960 1/1/1996

variable = 7 total phosphorus
mass balance term = 12 total outflow

Device	*volume (ac-ft)*	*load (lbs)*	*conc. (ppm)*	*removal (%)*
1 Pond	3,299,710	175,714	0.02	89.66
2 Splitter	3,226,847	86,718	0.01	0
3 Infilt.	2,337,225	20,801	0.003	66.87
4 Aquifer	16,326,710	401,650	0.009	0
5 Dummy	1,562,167	129,056	0.03	0
49 Overall	17,888,870	530,705	0.011	74.77

Appendix C. TDM Case Study P8 Inputs

Pre-developed Site

Calculation of Curve Numbers

BASIN 1	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Forest/Woods	8467.00	2.09	73	152.7403
Total Area (ac.)	**2.09233**			
Weighted CN	**73**			

Watershed Properties and Inputs

Sub-basins	*Name*	*Area (ac)*	*CN*	*Outflow Device*	*Aquifer Device*
1	Basin1	2.09233	73.0	2	1

Device Properties and Inputs

Aquifer

Device No.	*Time of Conc. (hrs)*	*Outflow device*
1	1	0

Pipe/Manhole

Device No.	*Time of Conc. (hrs)*	*Outflow device*
2	1	0

Current Site

Calculation of Curve Numbers

BASIN1	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Forested/Wooded Area	3977.40	0.98288	73	71.7502
Paved Area	4489.60	1.10945	98	108.7264
Total Area (ac.)	**2.09233**			
Weighted CN	**86.26**			

Watershed Properties and Inputs

Sub-basins	*Name*	*Area (ac)*	*CN*	*Outflow Device*	*Aquifer Device*
1	Basin1	2.09233	86.3	2	1

Device Properties and Inputs

Aquifer

Device No.	*Time of Conc. (hrs)*	*Outflow device*
1	1	0

Pipe/Manhole

Device No.	*Time of Conc. (hrs)*	*Outflow device*
2	1	0

Proposed Site

Curve Number Calculations

BASIN 1	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Sub-basin 1	180.60	0.04463	73	3.2578
Sub-basin 2	351.10	0.08676	98	8.5024
Total Area (ac.)	**0.13139**			
Weighted CN	**89.51**			

BASIN 2	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Sub-basin3	618.75	0.15290	73	11.1614
Sub-basin4	1152.00	0.28467	73	20.7806
Sub-basin5	913.20	0.22566	98	22.1144
Sub-basin6	754.60	0.18647	73	13.6120
Sub-basin7	1237.40	0.30577	98	29.9653
Sub-basin8	286.30	0.07075	74	5.2352
Total Area (ac.)	**1.22620**			
Weighted CN	**83.89**			

BASIN 3	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Sub-basin9	1071.00	0.26465	98	25.9357
Sub-basin10	220	0.05436	74	4.0229
Total Area (ac.)	**0.31901**			
Weighted CN	**93.91**			

BASIN 4	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Sub-basin 11	196.20	0.04848	73	3.5392
Total Area (ac.)	**0.04848**			
Weighted CN	**73**			

BASIN 5	*Area (m^2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Sub-basin12	574.30	0.14191	73	10.3596
Sub-basin13	414.80	0.10250	98	10.0449
Total Area (ac.)	**0.24441**			
Weighted CN	**83.48**			

BASIN 6	*Area (m2)*	*Area (ac.)*	*CN*	*Area*CN (ac.)*
Sub-basin14	232.60	0.05748	73	4.1958
Sub-basin15	251.60	0.06217	98	6.0928
Total Area (ac.)	**0.11965**			
Weighted CN	**85.99**			

Watershed Properties and Inputs

Basins	*Name*	*Area (ac)*	*CN*	*Outflow Device*	*Aquifer Device*
1	Basin1	0.13447	89.2	1	8
2	Basin2	1.22620	83.9	2	8
3	Basin3	0.31901	93.9	3	8
4	Basin4	0.04848	73.0	9	8
5	Basin5	0.24441	83.5	9	8
6	Basin6	0.11965	86.0	9	8

Device Properties and Inputs

Hydrological Soil Properties Classified by Soil Texture

Texture Class	*Hydrologic Soil Grouping*	*Minimum Infiltration Rate (in/hr)*	
Sand	A	6	Ammended Soil
Silt Loam	C	0.27	Natural Soil

Rain Gardens (Ammended Soil)

Device No.	*Geometry*	*Area (ac.)*	*Flood Pool Height (ft.)*	*Volume (ac-ft)*	*Weir Length (ft.)*	*Weir Discharge Coefficient*	*Outflow Device Number*		
							Infiltration	*Normal*	*Overflow*
2	rectangular	0.07075	0.492	0.0348	211	3.3	3	5	5
5	rectangular	0.05436	0.492	0.0267	37.4	3.3	6	9	9

Flow Splitters

Device No.	*Time of Conc. (hrs)*	*Outflow device (h<x)*	*if h< x ft. otherwise*	*Outflow device (h>x)*
3	1	4	3.28	5
6	1	7	3.28	9

Infiltration Basins

Device No.	*Geometry*	*Area (ac.)*	*Storage Pool Area (ac.)*	*Storage Pool Volume (ac-ft)*	*Porosity*	*Overflow device*	*Exfiltrate*
1	rectangular	0.00309	0.00309	0.0101	0.3	9	8
4	rectangular	0.07075	0.070746	0.2320	0.3	5	8
7	rectangular	0.05436	0.05436	0.1783	0.3	9	8

Aquifer

Device No.	*Time of Conc. (hrs)*	*Outflow device*
8	1	0

Pipe/Manhole

Device No.	*Time of Conc. (hrs)*	*Outflow device*
9	1	0

Appendix D. TDM Case Study P8 Results

Pre-Developed Site

Inflows

Variable = Total Phosphorus
Mass balance term = total inflow

Device #	*Type*	*volume (ac-ft)*	*load (lbs)*	*conc (ppm)*	*removal (%)*
1	Aquifer	218.36	5.87	0.01	0
2	Pipe	53.54	28.34	0.195	0
49	Overall	271.9	34.22	0.046	0

Outflows

Variable = Total Phosphorus
Mass balance term = total outflow

Device #	*Type*	*volume (ac-ft)*	*load (lbs)*	*conc (ppm)*	*removal (%)*
1	Aquifer	218.36	5.87	0.01	0
2	Pipe	53.54	28.34	0.195	0
49	Overall	271.9	34.22	0.046	0

Current Site

Inflows

CURRENT_ACTON ACTON2.CAS 1/3/1960 1/1/1996

Variable = 7 Total Phosphorus
Mass balance term = 12 total inflow

Device #	*Type*	*volume (ac-ft)*	*load (lbs)*	*conc (ppm)*	*removal (%)*
1	Aquifer	176.83	4.76	0.01	0
2	Pipe	95.52	59.16	0.228	0
49	Overall	272.36	63.91	0.086	0

Outflows

CURRENT_ACTON ACTON2.CAS 1/3/1960 1/1/1996

Variable = 7 Total Phosphorus
Mass balance term = 12 total outflow

Device #	*Type*	*volume (ac-ft)*	*load (lbs)*	*conc (ppm)*	*removal (%)*
1	Aquifer	176.83	4.76	0.01	0
2	Pipe	95.52	59.16	0.228	0
49	Overall	272.36	63.91	0.086	0

Proposed Site

Inflows

TDM proposed site w rain gardens TDM2.CAS 1/3/1960 1/1/1996

Variable = 7 Total Phosphorus
Mass balance term = 09 total inflow

Device #	*Type*	*volume (ac-ft)*	*load (lbs)*	*conc (ppm)*	*removal (%)*
1	Infiltration Basin	7.17	4.65	0.238	45.83
2	Detention Pond	49.89	29.94	0.221	90.43
3	Splitter	71.07	17.54	0.091	0
4	Infiltration Basin	60.32	15.13	0.092	85.55
5	Detention Pond	21.1	5.51	0.096	87.7
6	Splitter	20.56	0.2	0.004	0
7	Infiltration Basin	20.53	0.2	0.004	89.26
8	Aquifer	246.75	5.38	0.008	0
9	Pipe/Manhole	20.94	12.66	0.223	0
49	Overall	267.74	65.35	0.09	72.04

Outflows

TDM proposed site w/ rain gardens TDM2.CAS 1/3/1960 1/1/1996

Variable = 7 Total Phosphorus
Mass balance term = 12 total outflow

Device #	*Type*	*volume (ac-ft)*	*load (lbs)*	*conc (ppm)*	*removal (%)*
1	Infiltration Basin	7.17	2.49	0.128	45.83
2	Detention Pond	49.89	2.8	0.021	90.43
3	Splitter	71.07	17.56	0.091	0
4	Infiltration Basin	60.3	2.15	0.013	85.55
5	Detention Pond	21.1	0.65	0.011	87.7
6	Splitter	20.56	0.2	0.004	0
7	Infiltration Basin	20.5	0.02	0	89.26
8	Aquifer	246.75	5.38	0.008	0
9	Pipe/Manhole	20.94	12.64	0.222	0
49	Overall	267.69	18.03	0.025	72.04